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Wireless Personal Area Networks

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Samsung, Intel, ETRI, CSUS Version of Draft IEEE802.15.7

IEEE Standard for
Information technology—
Telecommunications and information exchange between systems—
Local and metropolitan area networks—
Specific requirements—

Part 15.7: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Visible Light Wireless Personal Area Networks (WPANs)

1. Overview

Visible Light Communications (VLC) is envisioned to be used in a variety of applications generally falling into one of the following topology classifications: peer-to-peer, where peers may be fixed, mobile or vehicular mounted, and infrastructure-to-mobile/vehicular. For VLC in infrastructure topologies, it is essential to support communications features that coexist without interruption to the primary use of LEDs for lighting. In many cases, this lighting will be diffuse with overlapping footprints of coverage.

This document defines a standard for a visible light communications WPAN.

1.1 Scope

The scope of this standard is to define the physical layer (PHY) and medium access control (MAC) sublayer specifications for visible light communications wireless connectivity with fixed, portable, and moving devices operating in the personal operating space (POS).

1.2 Purpose

This document provides an international standard for a visible light communications PHY and MAC to satisfy an evolutionary set of industrial and consumer requirements for wireless personal area network (WPAN) communications.

2. References

3. Definitions

4. Acronyms and abbreviations

FOV Field of View

LED Light Emitting Diode

LOS Line of Sight

PWM Pulse Width Modulation

P2P Peer to Peer

R-RZ Reverse-Return to Zero

TDM Time Division Multiplexing

VLC Visible Light Communication

VPM Variable Pulse Position Modulation

5. General Description

5.1 Introduction

Visible Light Communication transmits data by intensity modulating LEDs and LDs faster than the persistence of the human eye. VLC merges LED lighting and data communications in applications such as area lighting, signboards, streetlights, vehicles, and traffic signals. This standard describes the use of VLC for WPAN. Some of the characteristics found in this standard are:

- Star or peer-to-peer operation
- Allocated 16-bit short or 64-bit extended addresses
- Optional allocation of guaranteed time slots (GTSs)
- Random access with optional collision avoidance.
- Fully acknowledged protocol for transfer reliability
- Link quality indication (LQI)

Two different device types can participate in an IEEE 802.15.7 network; a full-function device (FFD) and a reduced-function device (RFD). The FFD can operate in two modes serving as a personal area network coordinator or a device. An FFD can talk to RFDs or other FFDs, while an RFD can talk only to an FFD or in a broadcast-only mode.

5.2 Components of the IEEE 802.15.7 VLC-WPAN

A system conforming to this standard consists of several components. The most basic is the device. A device may be an RFD or an FFD. Two or more devices within a POS communicating on the same physical channel constitute a VLC-WPAN. To form a network a VLC-WPAN shall include at least one FFD, operating as the coordinator.

An IEEE 802.15.7 network is part of the WPAN family of standards although the coverage of the network may extend beyond the POS, which typically defines the WPAN.

A well-defined coverage area does not exist for wireless media in general, and VLC-WPAN in particular, because propagation characteristics are dynamic and uncertain. Small changes in position or direction may result in drastic differences in the signal strength or quality of the communication link. These effects occur whether a device is stationary or mobile, as moving objects may impact station-to-station propagation.

5.3 Network topologies

Depending on the application requirements, an IEEE 802.15.7 WPAN may operate in either of two topologies: the star topology or the peer-to-peer topology. Both are shown in Figure 1. How these topologies might relate to applications is discussed in annex B.

In the star topology the communication is established between devices and a single central controller, called the coordinator. A device typically has some associated application and is either the initiation point or the termination point for network communications. A coordinator may also have a specific application, but it can be used to initiate, terminate, or route communication around the network. All devices operating on a network of either topology shall have unique 64-bit addresses. This address may be used for direct communication within the WPAN, or a short address may be allocated by the coordinator when the device associates and used instead. The coordinator might often be mains powered, while the devices will most likely will be battery powered.

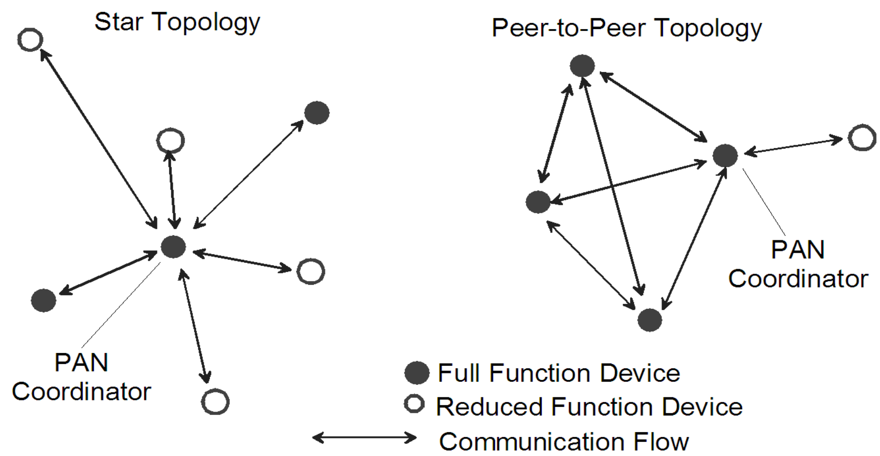


Figure 1—Star and peer-to-peer topology examples

The peer-to-peer topology also has a coordinator; however, it differs from the star topology in that any device may communicate with any other device as long as they are in range of one another. A peer-to-peer network can be ad hoc, self-organizing, and self-healing. It may also allow multiple hops to route messages from any device to any other device on the network. Such functions can be added at the higher layer, but are not part of this standard.

Each independent WPAN selects a unique identifier. This WPAN identifier allows communication between devices within a network using short addresses.. The mechanism by which identifiers are chosen is outside the scope of this standard.

The network formation is performed by the higher layer, which is not part of this standard. However, 5.3.1 and 5.3.2 provide a brief overview on how each supported topology can be formed. Apart from the two topologies, IEEE 802.15.7 devices may also operate in a broadcast only mode without being part of a network, i.e., without being associated to any device or having any devices associated to them.

5.3.1 Star network formation

The basic structure of a star network is illustrated in Figure 1. After an FFD is activated, it can establish its own network and become the coordinator. All star networks operate independently from all other star networks currently in operation. This is achieved by choosing a WPAN identifier that is not currently used by any other network within the radio sphere of influence. Once the WPAN identifier is chosen, the coordinator allows other devices, potentially both FFDs and RFDs, to join its network. The higher layer can use the procedures described in 7.5.2 and 7.5.3 to form a star network.

5.3.2 Peer-to-peer network formation

In a peer-to-peer topology, each device is capable of communicating with any other device within its VLC transmission sphere of influence. One device is nominated as the coordinator, for instance, by virtue of being the first device to communicate on the channel. Further network structures are constructed out of the peer-to-peer topology and it is possible to impose topological restrictions on the formation of the network.

5.4 (Informative) Modulation Domain Spectrum

It will help the reader of this specification to understand such concepts as VLC CCA by thinking in the modulation domain. The "modulation domain" is based upon the premise (at the time of the writing of this specification) that VLC receivers are photodetector based and hence basically the receiver non-coherently detects the envelope of the lightwave carrier. The modulation domain is defined as what we observe at the output of the photodetector. So when the standard mentions detecting a carrier, the reference point for detecting said carrier is at the photodetector output, which was modulated on the lightwave carrier. That is, CCA is not detecting the presence of "light" but rather detecting the presence of modulation on a lightwave carrier (i.e. modulation domain). The following figure tries to better illustrate this concept.

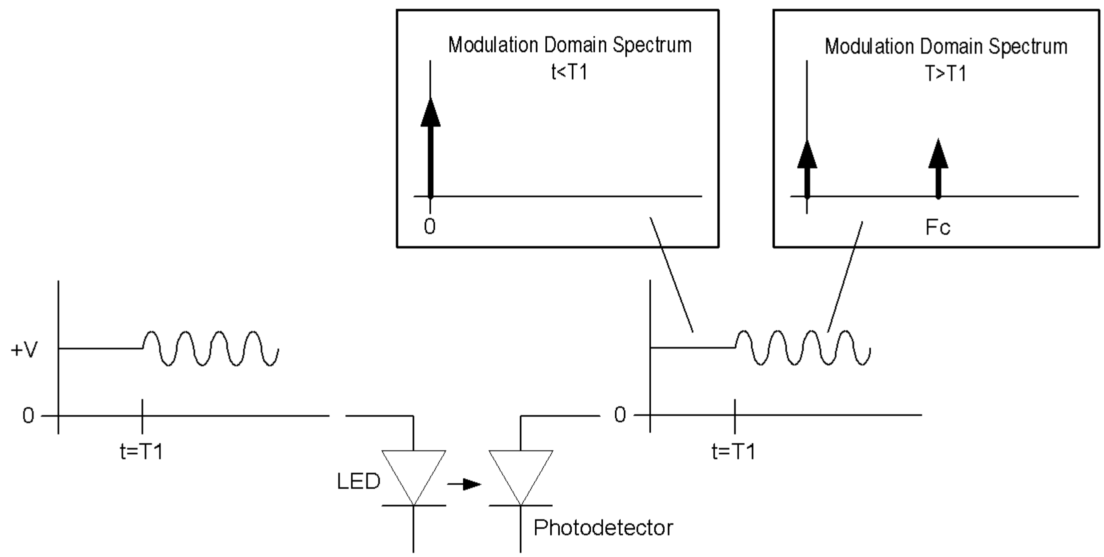


Figure 2—Illustration of Modulation Domain Spectrum

In Figure X we can see that the LED is "always on". When we say we do CCA we are implying that we want to detect when the modulation is applied, in our example at t=T1. As observed at the output of the photodetector, prior to t=T1 the spectrum is all at DC, while after t=T1 the spectrum is split between DC and the carrier frequency. So in this example CCA is not detecting if the LED is illuminated - it is illuminated all the time - rather the CCA is detecting when the modulation of interest is applied.

5.5 Architecture

The IEEE 802.15.7 architecture is defined in terms of a number of blocks in order to simplify the standard. These blocks are called layers. Each layer is responsible for one part of the standard and offers services to the higher layers. The layout of the blocks is based on the open systems interconnection (OSI) seven-layer model (see ISO/IEC 7498-1:1994 [B13]).

The interfaces between the layers serve to define the logical links that are described in this standard.

An VLC WPAN device comprises a PHY, which contains the light transceiver along with its low-level control mechanism, and a MAC sublayer that provides access to the physical channel for all types of transfer. Figure 3 shows these blocks in a graphical representation, which are described in more detail in 5.4.1 and 5.4.2

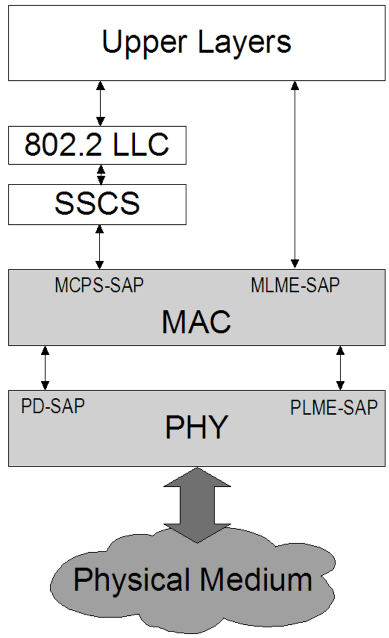


Figure 3—VLC-WPAN device architecture

The upper layers, shown in Figure 3, consist of a network layer, which provides network configuration, manipulation, and message routing, and an application layer, which provides the intended function of the device. The definition of these upper layers is outside the scope of this standard. An IEEE 802.2 Type 1 logical link control (LLC) can access the MAC sublayer through the service-specific convergence sublayer (SSCS), defined in Annex A. The VLC-WPAN architecture can be implemented either as embedded devices or as devices requiring the support of an external device such as a PC.

5.5.1 PHY

The VLC PHY consists of two parts: VLC transmit module and the VLC receive module. At the transmit module the encoded data is transformed to optical signal and that optical signal is transmitted by the light source to the receive module. The signal is detected into an electric signal by the detector and amplified. Finally, the data can be acquired via the decoder.

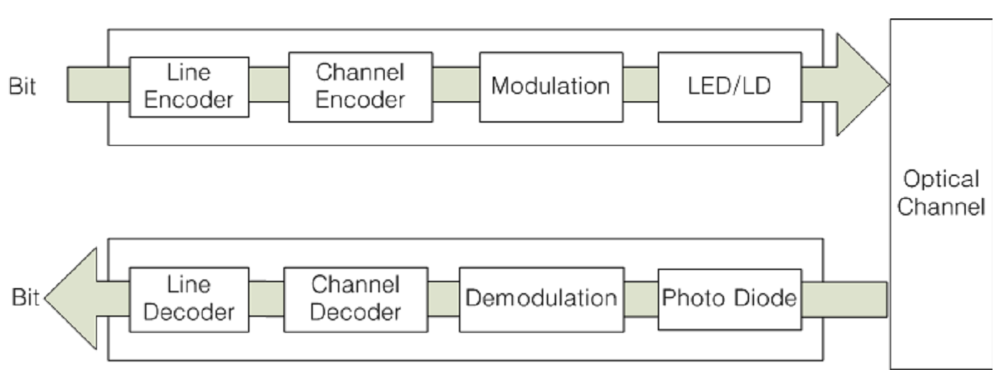


Figure 4—LED lighting source being used for VLC transmission and reception

The PHY layer supports two PHY types:

- PHY TYPE 1 - 10 kbps to 100 kbps

- PHY TYPE 2 - 3.2 Mbps to 96 Mbps

5.5.1.1 PHY TYPE 1

This PHY type is intended for longer range, lower data rate applications. This mode uses OOK and VPM modulation at a chipping rate of 200 kcps and 600 kcps. For OOK the burst data rate is 100 kbps without additional coding. Additional coding is used to achieve data rates of 50 kbps and 25 kbps. The basic link establishment rate is 25 kbps. For VPM, the burst data rate is 400 kbps without additional coding and 200 kbps with coding.

5.5.1.2 PHY TYPE 2

This PHY type is intended for short range, high data rate applications. This mode uses OOK, VPM and CCM. The basic link establishment rate is 3.2 Mbps.

5.5.1.3 CCM PHY Option

This PHY Option is intended for applications using CCM that have multiple light sources and detectors. The link establishment uses OOK. The basic link establishment rate is 3.2 Mbps using PHY type 2.

5.5.1.4 Coexistence Between PHY TYPES

The PHY types can co-exist but do not need to interoperate.

5.5.1.4.1 PHY TYPES 1 and 2 (Ed. Note: need to add coexistance with CCM on here also)

PHY types 1 and 2 occupy different spectral regions in the modulation domain spectrum which hence gives them FDM as a coexistence mechanism.

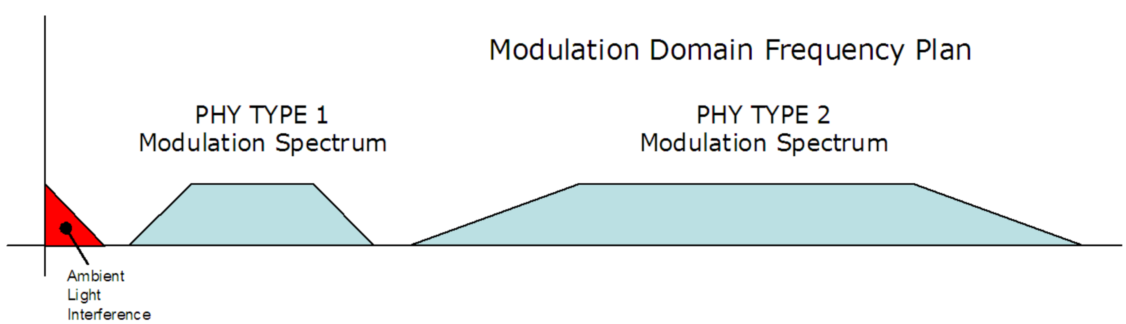


Figure 5—FDM separation of the PHY types in the modulation domain

5.5.1.5 Frame Flicker Compensation

During the packet transfer time the average optical power may change. To maintain a constant output power between packets a light source transmission is initiated that maintains this change in optical power. This is called frame flicker compensation and is used by both PHY types.

5.5.1.6 Accommodation of Light Dimmers

The information in regards to light dimming requirements is intercepted by the VLC modulator as shown below.

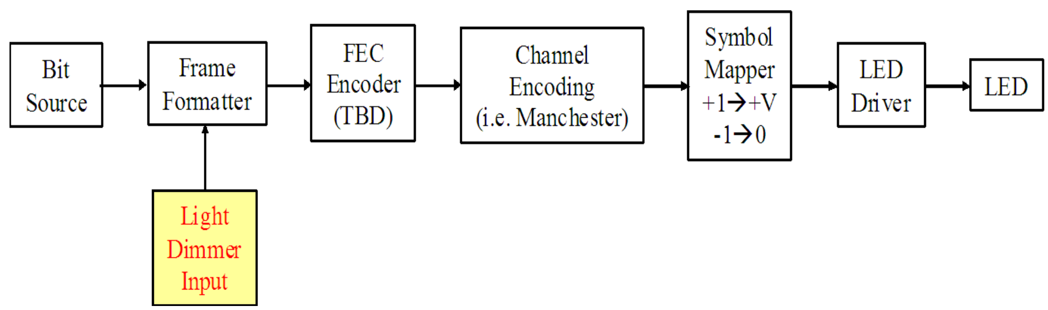


Figure 6—Accommodation of Light Dimmer during Packet Transfer Time [Delete Manchester from figure, Also, in case of VPM, the dimmer input is used for the modulation and not just for frame formatting]

Appropriate adjustments are made to the light transmission during data transmissions, and in between data transmissions, to reduce the average intensity of the light as put the dimmer input.

5.5.2 MAC sublayer

The MAC sublayer provides two services: the MAC data service and the MAC management service interfacing to the MAC sublayer management entity (MLME) service access point (SAP) (known as MLME-SAP). The MAC data service enables the transmission and reception of MAC protocol data units (MPDUs) across the PHY data service.

The features of the MAC sublayer are beacon management, channel access, GTS management, frame validation, acknowledged frame delivery, association, and disassociation. In addition, the MAC sublayer provides hooks for implementing application-appropriate security mechanisms.

Clause 7 contains the specifications for the MAC sublayer.

5.6 Functional overview

A brief overview of the general functions of a VLC WPAN is given in 5.5.1 through 5.6.8 and includes information on the superframe structure, the data transfer model, the frame structure, robustness, power consumption considerations, precision ranging, and security.

5.6.1 Superframe structure

This standard allows the optional use of a superframe structure. The format of the superframe is defined by the coordinator. The superframe is bounded by network beacons sent by the coordinator [see Figure 4a)] and is divided into equally sized slots. Optionally, the superframe can have an active and an inactive portion [see Figure 4b)]. During the inactive portion, the coordinator may enter a low-power mode. The beacon frame is transmitted in the first slot of each superframe. If a coordinator does not wish to use a superframe structure, it will turn off the beacon transmissions. The beacons are used to synchronize the attached devices, to identify the WPAN, and to describe the structure of the superframes. Any device wishing to communicate during the contention access period (CAP) between two beacons competes with other devices using slotted random access .

All transactions are completed by the time of the next network beacon.

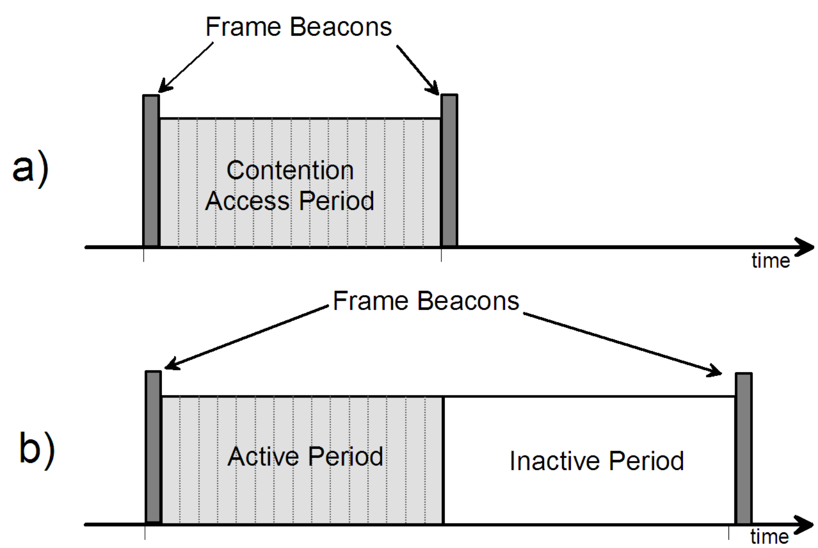


Figure 7—Superframe structure without GTSs

For low-latency applications or applications requiring specific data bandwidth, the coordinator may dedicate portions of the active superframe to that application. These portions are called guaranteed time slots (GTSs). The GTSs form the contention-free period (CFP), which always appears at the end of the active superframe starting at a slot boundary immediately following the CAP, as shown in Figure 5. The coordinator may allocate up a number of these GTSs, and a GTS may occupy more than one slot period. However, a sufficient portion of the CAP remains for contention-based access of other networked devices or new devices wishing to join the network. All contention-based transactions is completed before the CFP begins. Also each device transmitting in a GTS ensures that its transaction is complete before the time of the next GTS or the end of the CFP. More information on the superframe structure can be found in 7.5.1.1

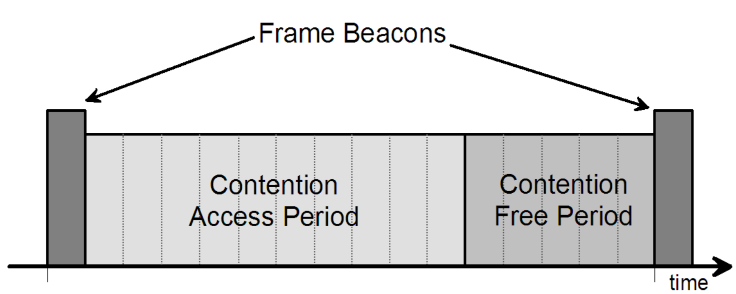


Figure 8—Superframe structure with GTSs

5.6.2 Data transfer model

Three types of data transfer transactions exist. The first one is the data transfer to a coordinator in which a device transmits the data. The second transaction is the data transfer from a coordinator in which the device receives the data. The third transaction is the data transfer between two peer devices. In star topology, only two of these transactions are used because data may be exchanged only between the coordinator and a device. In a peer-to-peer topology, data may be exchanged between any two devices on the network; consequently all three transactions may be used in this topology.

The mechanisms for each transfer type depend on whether the network supports the transmission of beacons. A beacon-enabled VLC WPAN is used in networks that either require synchronization or support for low-latency devices, such as PC peripherals. If the network does not need synchronization or support for low latency devices, it can elect not to use the beacon for normal transfers. However, the beacon is still required for network discovery. The structure of the frames used for the data transfer is specified in 7.2.

5.6.3 Data transfer to a coordinator

When a device wishes to transfer data to a coordinator in a beacon-enabled VLC WPAN, it first listens for the network beacon. When the beacon is found, the device synchronizes to the superframe structure. At the appropriate time, the device transmits its data frame, using slotted random access to the coordinator. The coordinator may acknowledge the successful reception of the data by transmitting an optional acknowledgment frame. This sequence is summarized in Figure 6.

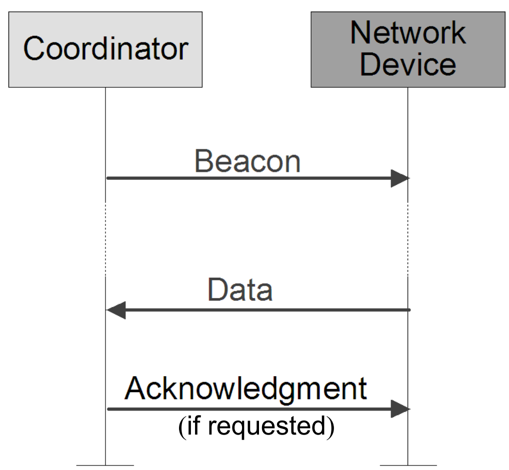


Figure 9—Communication to a coordinator in a beacon-enabled VLC WPAN

When a device wishes to transfer data in a nonbeacon-enabled VLC WPAN, it simply transmits its data frame, using unslotted random access, to the coordinator. The coordinator acknowledges the successful reception of the data by transmitting an optional acknowledgment frame. The transaction is now complete. This sequence is summarized in Figure 7.

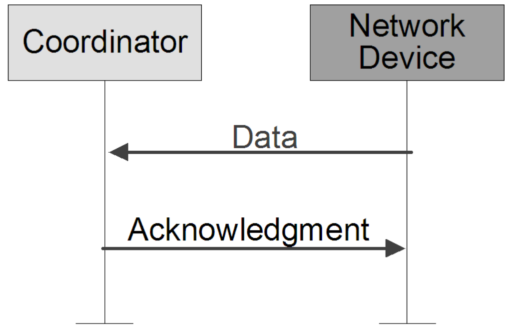


Figure 10—Communication to a coordinator in a nonbeacon-enabled VLC WPAN

5.6.3.1 Data transfer from a coordinator

When the coordinator wishes to transfer data to a device in a beacon-enabled VLC WPAN, it indicates in the network beacon that the data message is pending. The device periodically listens to the network beacon and, if a message is pending, transmits a MAC command requesting the data, using slotted random access . The coordinator acknowledges the successful reception of the data request by transmitting an acknowledgment frame. The pending data frame is then sent using slotted random access , or, if possible, immediately after the acknowledgment (see 7.5.6.3). The device may acknowledge the successful reception of the data by transmitting an optional acknowledgment frame. The transaction is now complete. Upon successful completion of the data transaction, the message is removed from the list of pending messages in the beacon. This sequence is summarized in Figure 8.

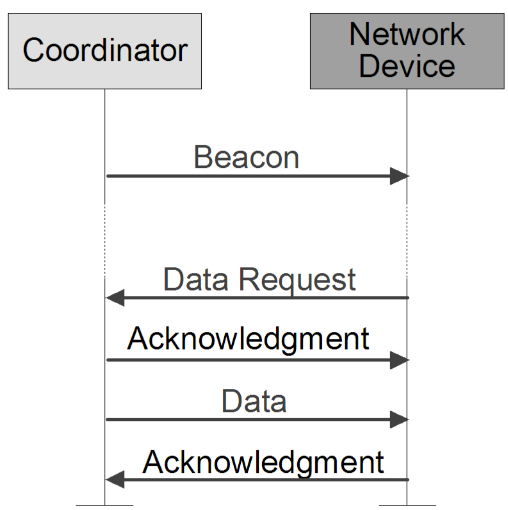


Figure 11—Communication from a coordinator a beacon-enabled VLC WPAN

When a coordinator wishes to transfer data to a device in a nonbeacon-enabled VLC WPAN, it stores the data for the appropriate device to make contact and request the data. A device may make contact by transmitting a MAC command requesting the data, using unslotted random access to its coordinator at an application-defined rate. The coordinator acknowledges the successful reception of the data request by transmitting an acknowledgment frame. If a data frame is pending, the coordinator transmits the data frame, using unslotted random access to the device. If a data frame is not pending, the coordinator indicates this fact either in the acknowledgment frame following the data request or in a data frame with a zero-length payload (see 7.5.6.3). If requested, the device acknowledges the successful reception of the data frame by transmitting an acknowledgment frame. This sequence is summarized in Figure 9.

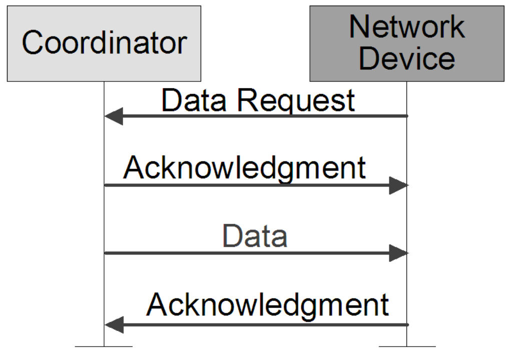


Figure 12—Communication from a coordinator in a nonbeacon-enabled VLC WPAN

5.6.3.2 Peer-to-peer data transfers

In a peer-to-peer VLC WPAN, every device may communicate with every other device in its radio sphere of influence. In order to do this effectively, the devices wishing to communicate will need to either receive constantly or synchronize with each other. In the former case, the device can simply transmit its data usingrandom access . In the latter case, other measures need to be taken in order to achieve synchronization. Such measures are beyond the scope of this standard.

5.6.4 Frame structure

The frame structures have been designed to keep the complexity to a minimum while at the same time making them sufficiently robust for transmission on a noisy channel. Each successive protocol layer adds to the structure with layer-specific headers and footers. This standard defines four frame structures:

- A beacon frame, used by a coordinator to transmit beacons
- A data frame, used for all transfers of data
- An acknowledgment frame, used for confirming successful frame reception
- A MAC command frame, used for handling all MAC peer entity control transfers

The structure of each of the four frame types is described in 5.6.4.1 through 5.6.4.5. The diagrams in these subclauses illustrate the fields that are added by each layer of the protocol.

5.6.4.1 Beacon frame

Figure 10 shows the structure of the beacon frame, which originates from within the MAC sublayer. A coordinator can transmit network beacons in a beacon-enabled VLC WPAN. The MAC payload contains the superframe specification, GTS fields, pending address fields, and beacon payload (see 7.2.2.1). The MAC payload is prefixed with a MAC header (MHR) and appended with a MAC footer (MFR). The MHR contains the MAC Frame Control field, beacon sequence number (BSN), addressing fields, and optionally the auxiliary security header. The MFR contains a 16-bit frame check sequence (FCS). The MHR, MAC payload, and MFR together form the MAC beacon frame (i.e., MPDU).

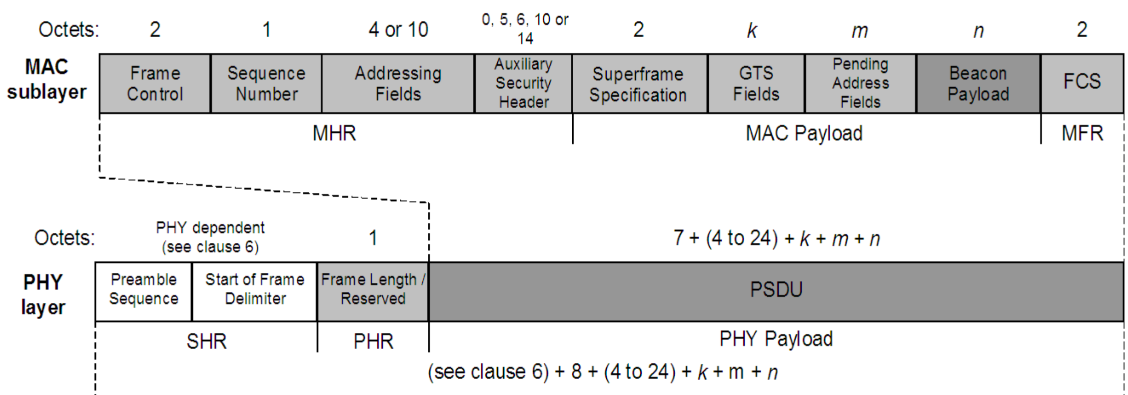


Figure 13—Figure 13-Schematic view of the beacon frame and the PHY packet (SFD is not needed based on current preamble design. Need to adjust other figures based on this as well)

The MAC beacon frame is then passed to the PHY as the PHY service data unit (PSDU), which becomes the PHY payload. The PHY payload is prefixed with a synchronization header (SHR), containing the Preamble Sequence and Start-of-Frame Delimiter (SFD) fields, and a PHY header (PHR) containing the length of the PHY payload in octets. The SHR, PHR, and PHY payload together form the PHY packet (i.e., PPDU).

5.6.4.2 Data frame

Figure 11 shows the structure of the data frame, which originates from the upper layers.

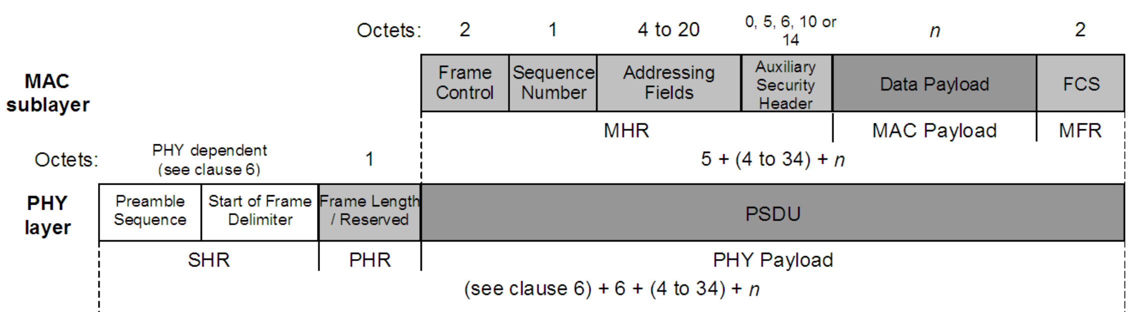


Figure 14—Schematic view of the data frame and the PHY packet

The data payload is passed to the MAC sublayer and is referred to as the MAC service data unit (MSDU). The MAC payload is prefixed with an MHR and appended with an MFR. The MHR contains the Frame Control field, data sequence number (DSN), addressing fields, and optionally the auxiliary security header. The MFR is composed of a 16-bit FCS. The MHR, MAC payload, and MFR together form the MAC data frame, (i.e., MPDU).

The MPDU is passed to the PHY as the PSDU, which becomes the PHY payload. The PHY payload is prefixed with an SHR, containing the Preamble Sequence and SFD fields, and a PHR containing the length of the PHY payload in octets. The preamble sequence and the data SFD enable the receiver to achieve symbol synchronization. The SHR, PHR, and PHY payload together form the PHY packet, (i.e., PPDU).

5.6.4.3 Acknowledgment frame

Figure 12 shows the structure of the acknowledgment frame, which originates from within the MAC sublayer. The MAC acknowledgment frame is constructed from an MHR and an MFR; it has no MAC payload. The MHR contains the MAC Frame Control field and DSN. The MFR is composed of a 16-bit FCS. The MHR and MFR together form the MAC acknowledgment frame (i.e., MPDU).

The MPDU is passed to the PHY as the PSDU, which becomes the PHY payload. The PHY payload is prefixed with the SHR, containing the Preamble Sequence and SFD fields, and the PHR containing the length of the PHY payload in octets. The SHR, PHR, and PHY payload together form the PHY packet, (i.e., PPDU).

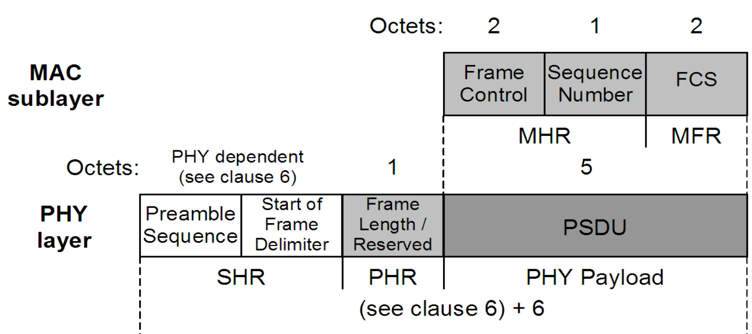


Figure 15—Schematic view of the acknowledgment frame and the PHY packet

5.6.4.4 MAC command frame

Figure 13 shows the structure of the MAC command frame, which originates from within the MAC sublayer. The MAC payload contains the Command Type field and the command payload (see 7.2.2.4). The MAC payload is prefixed with an MHR and appended with an MFR. The MHR contains the MAC Frame Control field, DSN, addressing fields, and optionally the auxiliary security header. The MFR contains a 16-bit FCS. The MHR, MAC payload, and MFR together form the MAC command frame, (i.e., MPDU).

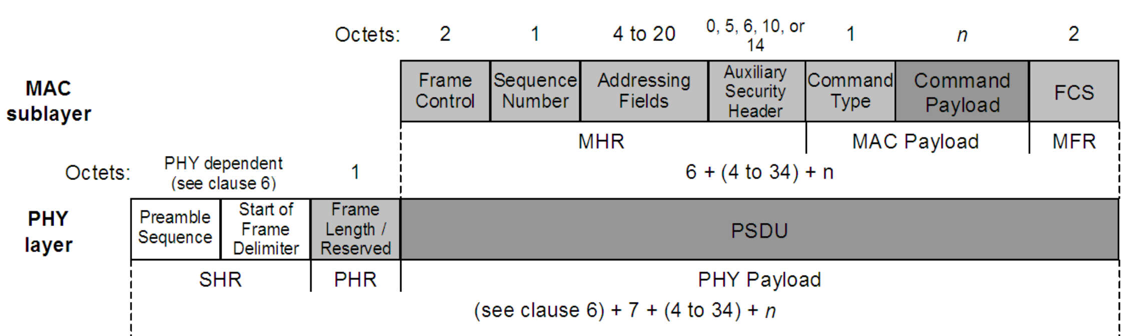


Figure 16—Schematic view of the MAC command frame and the PHY packet

The MPDU is then passed to the PHY as the PSDU, which becomes the PHY payload. The PHY payload is prefixed with an SHR, containing the Preamble Sequence and SFD fields, and a PHR containing the length of the PHY payload in octets. The preamble sequence enables the receiver to achieve symbol synchronization. The SHR, PHR, and PHY payload together form the PHY packet, (i.e., PPDU).

5.6.4.5 Visible/Dimming frame

Figure 5 shows the structure of the visible/dimming frame.

Preamble	Header	HCS	Visible/Dimming pattern

Figure 17—Visible/Dimming Frame

A VF (Visible Frame) is used to inform link status (such as misalignment between the two devices, light direction or sending data status). This frame can also be used for dimming function.

5.6.5 Improving probability of successful delivery

The IEEE 802.15.7 VLC WPAN employs various mechanisms to improve the probability of successful data transmission. These mechanisms are the random access, frame acknowledgment, and data verification and are briefly discussed in 5.5.4.1 through 5.5.4.4.

5.6.5.1 Random access mechanism

The IEEE 802.15.7 VLC WPAN uses two types of channel access mechanism, depending on the network configuration. Nonbeacon-enabled PANs use an unslotted random channel access mechanism, as described in 7.5.1. Each time a device wishes to transmit data frames or MAC commands, it waits for a random period. Following the random backoff, the device transmits its data. If the optional carrier sense mechanism is active and the channel is found to be busy following the random backoff, the device waits for another random period before trying to access the channel again. Acknowledgment frames are sent without using a random access mechanism.

Beacon-enabled PANs use a slotted random channel access mechanism, where the backoff slots are aligned with the start of the beacon transmission. The backoff slots of all devices within one VLC WPAN are aligned to the coordinator. Each time a device wishes to transmit data frames during the CAP, it locates the boundary of the next backoff slot and then waits for a random number of backoff slotsIf theoptional collision avoidance mechanism is active and the channel is busy, following this random backoff, the device waits for another random number of backoff slots before trying to access the channel again. If the channel is idle or the optional carrier sense mechanism is not active, the device begins transmitting on the next available backoff slot boundary. Acknowledgment and beacon frames are sent without using a random access mechanism.

5.6.5.2 Frame acknowledgment

A successful reception and validation of a data or MAC command frame can be optionally confirmed with an acknowledgment, as described in 7.5.6.4. If the receiving device is unable to handle the received data frame for any reason, the message is not acknowledged.

If the originator does not receive an acknowledgment after some period, it assumes that the transmission was unsuccessful and retries the frame transmission. If an acknowledgment is still not received after several retries, the originator can choose either to terminate the transaction or to try again. When the acknowledgment is not required, the originator assumes the transmission was successful.

5.6.5.3 Data verification

In order to detect bit errors, an FCS mechanism employing a 16-bit International Telecommunication Union-Telecommunication Standardization Sector (ITU-T) cyclic redundancy check (CRC) is used to detect errors in every frame.

The FCS mechanism is discussed in 7.2.1.9.

5.6.6 Power consumption considerations

TBD

5.7 Regulations (Informative)

There are two eye/skin safety issues related to VLCregulations:

- Visible light flickering
- Visible light strength

Flicker is an impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time [IEC 1000-3-3]. Critical fusion frequency (CFF, a.k.a. flicker fusion threshold) is a frequency at which an intermittent light stimulus appears to be completely steady to the observer.

Flicker may cause harmful health impacts: visual discomfort [Stone, 1990], eyestrain [Lindner, 1993], headache [Wilkins, 1989], increase in speed and decrease in performance of mental tasks (reading comprehension) [Küller, 1998], repetitive behavior of autistic children [Colman, 1976], and photosensitive epilepsy (2% of all epilepsy cases) [Harding, 1995].

It is suggested that the modulation frequency of a VLC transmitter be higher than CFF (critical fusion frequency) threshold.

The CFF (critical fusion frequency) thresholds are:

"The 1/minimum flickering frequency is 200 Hz (= 5ms).

"Brightness of each Maximum Flickering Time Period (MFTP) must be all equal.

This standard does not specify flicker nor light strength; rather, the reader is referred to local regulatory limits.

5.7.1 Security

<editor's note: this section and the security mechanism needs to be reviewed for its applicability to VLC>

From a security perspective, wireless ad hoc networks are no different from any other wireless network. They are vulnerable to passive eavesdropping attacks and potentially even active tampering because physical access to the wire is not required to participate in communications. The very nature of ad hoc networks and their cost objectives impose additional security constraints, which perhaps make these networks the most difficult environments to secure. Devices are low-cost and have limited capabilities in terms of computing power, available storage, and power drain; and it cannot always be assumed they have a trusted computing base nor a high-quality random number generator aboard. Communications cannot rely on the online availability of a fixed infrastructure and might involve short-term relationships between devices that may never have communicated before. These constraints might severely limit the choice of cryptographic algorithms and protocols and would influence the design of the security architecture because the establishment and maintenance of trust relationships between devices need to be addressed with care. In addition, battery lifetime and cost constraints put severe limits on the security overhead these networks can tolerate, something that is of far less concern with higher bandwidth networks. Most of these security architectural elements can be implemented at higher layers and may, therefore, be considered to be outside the scope of this standard.

The cryptographic mechanism in this standard is based on symmetric-key cryptography and uses keys that are provided by higher layer processes. The establishment and maintenance of these keys are outside the scope of this standard. The mechanism assumes a secure implementation of cryptographic operations and secure and authentic storage of keying material.

The cryptographic mechanism provides particular combinations of the following security services:

- Data confidentiality: Assurance that transmitted information is only disclosed to parties for which it is intended.

- Data authenticity: Assurance of the source of transmitted information (and, hereby, that information was not modified in transit).

- Replay protection: Assurance that duplicate information is detected.

The actual frame protection provided can be adapted on a frame-by-frame basis and allows for varying levels of data authenticity (to minimize security overhead in transmitted frames where required) and for optional data confidentiality. When nontrivial protection is required, replay protection is always provided.

Cryptographic frame protection may use a key shared between two peer devices (link key) or a key shared among a group of devices (group key), thus allowing some flexibility and application-specific tradeoffs between key storage and key maintenance costs versus the cryptographic protection provided. If a group key is used for peer-to-peer communication, protection is provided only against outsider devices and not against potential malicious devices in the key-sharing group.

For more detailed information on the cryptographic security mechanisms used for protected MAC frames following this standard, refer to Clause 7.

5.8 Concept of primitives

This subclause provides a brief overview of the concept of service primitives. Refer to IEEE Std 802.2-1998 for more detailed information.

The services of a layer are the capabilities it offers to the user in the next higher layer or sublayer by building its functions on the services of the next lower layer. This concept is illustrated in Figure 14, showing the service hierarchy and the relationship of the two correspondent N-users and their associated N-layer (or sublayer) peer protocol entities.

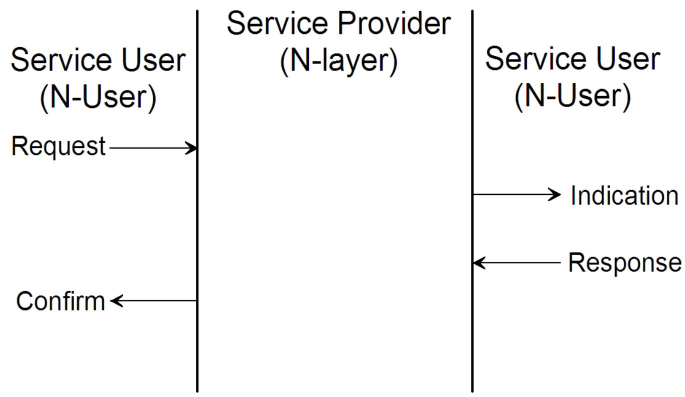


Figure 18—Service primitives

The services are specified by describing the information flow between the N-user and the N-layer. This information flow is modeled by discrete, instantaneous events, which characterize the provision of a service. Each event consists of passing a service primitive from one layer to the other through a layer SAP associated with an N-user. Service primitives convey the required information by providing a particular service. These service primitives are an abstraction because they specify only the provided service rather than the means by which it is provided. This definition is independent of any other interface implementation.

Services are specified by describing the service primitives and parameters that characterize it. A service may have one or more related primitives that constitute the activity that is related to that particular service. Each service primitive may have zero or more parameters that convey the information required to provide the service.

A primitive can be one of four generic types:

— Request: The request primitive is passed from the N-user to the N-layer to request that a service is initiated.

— Indication: The indication primitive is passed from the N-layer to the N-user to indicate an internal N-layer event that is significant to the N-user. This event may be logically related to a remote service request, or it may be caused by an N-layer internal event.

— Response: The response primitive is passed from the N-user to the N-layer to complete a procedure previously invoked by an indication primitive.

— Confirm: The confirm primitive is passed from the N-layer to the N-user to convey the results of one or more associated previous service requests.

6. PHY sublayer specification

This clause specifies three PHY options for IEEE 802.15.7. The PHY is responsible for the following tasks:

— Activation and deactivation of the VL transceiver

— LQI for received packets

— Channel selection

— Data transmission and reception

Constants and attributes that are specified and maintained by the PHY are written in the text of this clause in italics. Constants have a general prefix of “a”, e.g., aMaxPHYPacketSize, and are listed in Table X. Attributes have a general prefix of “phy”, e.g., phyCurrentChannel, and are listed in Table X.

6.1 General requirements and definitions

This subclause specifies requirements that are common to both of the IEEE 802.15.7 PHYs.

6.1.1 Operating wavelength range

A compliant device shall operate within the visible light spectrum defined as being from 380 nm to 780 nm.

6.1.2 Operating frequency range

A compliant device shall operate in one or several visible light frequency bands as shown in table X using the modulation and spreading formats summarized in Table Y.

Frequency band (nm)		Spectral width (nm)	Color	Proposed Code
380	450	70	pB	000
450	510	60	B, BG	001
510	560	50	G	010
560	600	40	yG,gY,	011
600	650	50	rO	100
650	710	60	R	101
710	780	70	R	110
			Reserved	111

This standard is intended to conform with established regulations in Europe, Japan, Canada, and the United States. The regulatory documents listed below are for information only and are subject to change and revisions at any time. IEEE 802.15.7 devices shall also comply with specific regional legislation. Additional regulatory information is provided in Annex X.

Canada:

Europe:

Japan:

Korea:

United States:

6.1.3 Operating modes

A compliant IEEE802.15.7 PHY shall implement at least one of the following PHY modes.

Table 1—PHY Type 1 Operating Modes

	Optical rate	Modulation	Line Coding	FEC	Data rate
PHY 1	200 kHz	OOK	Manchester	1/16	6.25 kbps
	200 kHz	OOK	Manchester	1/8	12.5 kbps
	200 kHz	OOK	Manchester	1/4	25 kbps
	200 kHz	OOK	Manchester	1/2	50 kbps
	200 kHz	OOK	Manchester	1	100 kbps
	600 kHz	VPM	4B6B	1/2	200 kbps
	600 kHz	VPM	4B6B	1	400 kbps

Table 2—PHY Type 2 Operating Modes

	Optical rate	Modulation	Line coding	FEC	Data rate
PHY II	6 MHz	VPM	4B6B	4/5	3.2 Mbps
	12 MHz	VPM	4B6B	4/5	6.4 Mbps
	24 MHz	OOK	8B10B	1/2	9.6 Mbps
	60 MHz	OOK	8B10B	1/2	24 Mbps
	60 MHz	OOK	8B10B	4/5	38.4 Mbps
	120 MHz	OOK	8B10B	4/5	76.8 Mbps
	120 MHz	OOK	8B10B	1	96 Mbps

Table 3—PHY Type CCM Operating Modes

	Optical rate	Modulation	FEC	Data rate
CCM	12 MHz	4 CCM	1/2	12 Mbps
	12 MHz	8 CCM	1/2	18 Mbps
	24 MHz	4 CCM	1/2	24 Mbps
	24 MHz	8 CCM	1/2	36 Mbps
	24 MHz	16 CCM	1/2	48 Mbps
	24 MHz	8 CCM	1	72 Mbps
	24 MHz	16 CCM	1	96 Mbps

6.1.4 Channel assignments and numbering

TBD

6.1.5 Optical power measurement

TBD

6.1.6 Transmit power

The maximum transmit power shall conform with local regulations. Refer to Annex X for additional information on regulatory limits. A compliant device shall have its nominal transmit power level indicated by its PHY parameter, phyTransmitPower (see 6.4).

6.1.7 Receiver sensitivity definitions

The definitions in Table 2 are referenced by subclauses elsewhere in this standard regarding receiver sensitivity.

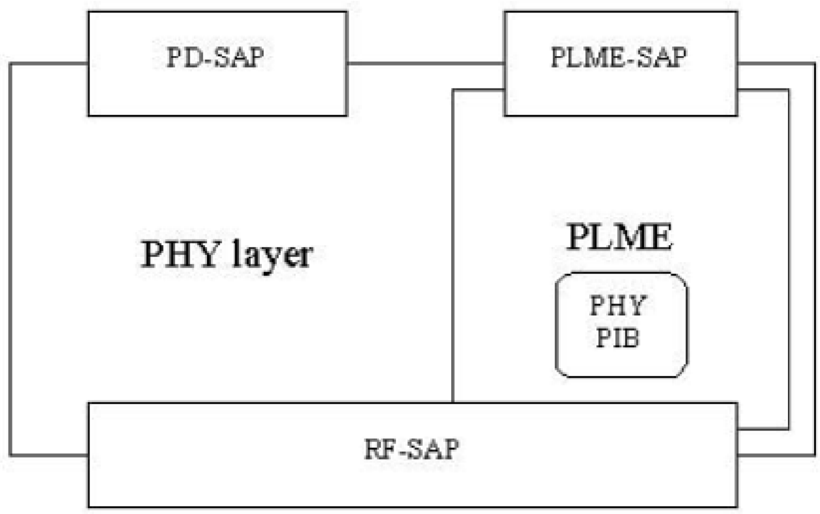
6.2 PHY service specifications

Table 4—Receiver sensitivity definitions

Term	Definition of term	Conditions
Packet error rate (PER)	Average fraction of transmitted packets that are not detected correctly.	- Average measured over random PSDU data.
Receiver sensitivity	Threshold input signal power that yields a specified PER.	- PSDU length = 20 octets - PER <1% - Optical power measured at photodetector - Interference not present

The PHY provides an interface between the MAC sublayer and the physical optical channel, via the VLC firmware and VLC hardware. The PHY conceptually includes a management entity called the PLME. This entity provides the layer management service interfaces through which layer management functions may be invoked. The PLME is also responsible for maintaining a database of managed objects pertaining to the PHY. This database is referred to as the PHY PAN information base (PIB).

Figure X depicts the components and interfaces of the PHY.



The PHY provides two services, accessed through two SAPs: the PHY data service, accessed through the PHY data SAP (PD-SAP), and the PHY management service, accessed through the PLME's SAP (PLME-SAP).

6.2.1 PHY data service

The PD-SAP supports the transport of MPDUs between peer MAC sublayer entities. Table 1 lists the primitives supported by the PD-SAP. These primitives are discussed in the subclauses referenced in the table.

Table 5—PD-SAP primitives

PD-SAP primitive	Request	Confirm	Indication
PD-DAtA	6.x.x.x	6.x.x.x	6.x.x.x

6.2.1.1 PD-DATA.request

The PD-DATA.request primitive requests the transfer of an MPDU (i.e., PSDU) from the MAC sublayer to the local PHY entity.

6.2.1.1.1 Semantics of the service primitive

The semantics of the PD-DATA.request primitive is as follows:

PD-DATA.request (

psduLength,

psdu

)

Table 2 specifies the parameters for the PD-DATA.request primitive.

Table 6—PD-DATA.request parameters

Name	Type	Valid range	Description
psduLength	Unsigned Integer	<=aMaxPHYPacketSize	The number of octets in the PSDU to be transmitted by the PHY entity.
psdu	Set of octets	-	The set of octets forming the PSDU to be transmitted by the PHY entity.

6.2.1.1.2 When generated

The PD-DATA.request primitive is generated by a local MAC sublayer entity and issued to its PHY entity to request the transmission of an MPDU.

6.2.1.1.3 Effect on receipt

The receipt of the PD-DATA.request primitive by the PHY entity will cause the transmission of the supplied PSDU. Provided the transmitter is enabled (TX_ON state), the PHY will first construct a PPDU, containing the supplied PSDU, and then transmit the PPDU. When the PHY entity has completed the transmission, it will issue the PD-DATA.confirm primitive with a status of SUCCESS.

If the PD-DATA.request primitive is received while the receiver is enabled (RX_ON state) or if the transceiver is disabled (TRX_OFF state), the PHY entity will issue the PD-DATA.confirm primitive with a status of RX_ON or TRX_OFF, respectively.

6.2.1.2 PD-DATA.confirm

The PD-DATA.confirm primitive confirms the end of the transmission of an MPDU (i.e., PSDU) from a local MAC sublayer entity to a peer MAC sublayer entity.

6.2.1.2.1 Semantics of the service primitive

The semantics of the PD-DATA.confirm primitive is as follows:

PD-DATA.confirm (

status

)

Table 3 specifies the parameters for the PD-DATA.confirm primitive.

Table 7—PD-DATA.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, RX_ON, or TRX_OFF	The result of the request to transmit a packet

6.2.1.2.2 When generated

The PD-DATA.confirm primitive is generated by the PHY entity and issued to its MAC sublayer entity in response to a PD-DATA.request primitive. The PD-DATA.confirm primitive will return a status of either SUCCESS, indicating that the request to transmit was successful, or an error code of RX_ON or TRX_OFF. The reasons for these status values are fully described in 6.2.1.1.3.

6.2.1.2.3 Effect on receipt

On receipt of the PD-DATA.confirm primitive, the MAC sublayer entity is notified of the result of its request to transmit. If the transmission attempt was successful, the status parameter is set to SUCCESS. Otherwise, the status parameter will indicate the error.

6.2.1.3 PD-DATA.indication

The PD-DATA.indication primitive indicates the transfer of an MPDU (i.e., PSDU) from the PHY to the local MAC sublayer entity.

6.2.1.3.1 Semantics of the service primitive

The semantics of the PD-DATA.indication primitive is as follows:

```
PD-DATA.indication          (
                            psduLength,
                            psdu,
                            ppduLinkQuality
                            )
```

Table 6 specifies the parameters for the PD-DATA.indication primitive.

Table 8—PD-DATA.indication parameters

Name	Type	Valid	Description
psduLength	Unsigned Integer	<=aMaxPHYPacketSize	The number of octets contained in the PSDU received by the PHY entity.
psdu	Set of octets	-	The set of octets forming the PSDU received by the PHY entity.
ppduLinkQuality	Integer	0x00-0 x ff	Link quality (LQ) value measured during reception of the PPDU (see 6.x.x).

6.2.1.3.2 When generated

The PD-DATA.indication primitive is generated by the PHY entity and issued to its MAC sublayer entity to transfer a received PSDU. This primitive will not be generated if the received psduLength field is zero or greater than aMaxPHYPacketSize.

6.2.1.3.3 Effect on receipt

On receipt of the PD-DATA.indication primitive, the MAC sublayer is notified of the arrival of an MPDU across the PHY data service.

6.2.2 PHY management service

The PLME-SAP allows the transport of management commands between the MLME and the PLME. Table 5 lists the primitives supported by the PLME-SAP. These primitives are discussed in the clauses referenced in the table.

Table 9—PLME-SAP primitives

PLME-SAP primitive	Request	Confirm
PLME-CCA	6.x.x.x	6.x.x.x
PLME-GET	6.x.x.x	6.x.x.x
PLME-SET-TRX-STATE	6.x.x.x	6.x.x.x
PLME-SET	6.x.x.x	6.x.x.x
PLME-DIMMER	6.x.x.x	6.x.x.x

6.2.2.1 PLME-CCA.request

The PLME-CCA.request primitive requests that the PLME perform a CCA as defined in 6.7.9.

6.2.2.1.1 Semantics of the service primitive

The semantics of the PLME-CCA.request primitive is as follows:

PLME-CCA.request ()

There are no parameters associated with the PLME-CCA.request primitive.

6.2.2.1.2 When generated

The PLME-CCA.request primitive is generated by the MLME and issued to its PLME whenever the random access algorithm requires an assessment of the channel.

6.2.2.1.3 Effect on receipt

If the receiver is enabled on receipt of the PLME-CCA.request primitive, the PLME will cause the PHY to perform a CCA. When the PHY has completed the CCA, the PLME will issue the PLME-CCA.confirm primitive with a status of either BUSY or IDLE, depending on the result of the CCA.

If the PLME-CCA.request primitive is received while the transceiver is disabled (TRX_OFF state) or if the transmitter is enabled (TX_ON state), the PLME will issue the PLME-CCA.confirm primitive with a status of TRX_OFF or TX_ON, respectively.

6.2.2.2 PLME-CCA.confirm

The PLME-CCA.confirm primitive reports the results of a CCA.

6.2.2.2.1 Semantics of the service primitive

The semantics of the PLME-CCA.confirm primitive is as follows:

PLME-CCA.confirm (

status

)

Table 8 specifies the parameters for the PLME-CCA.confirm primitive.

Table 10—PLME-CCA.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	TRX_OFF, TX_ON, BUSY, or IDLE	The result of the request to perform a CCA.

6.2.2.2.2 When generated

The PLME-CCA.confirm primitive is generated by the PLME and issued to its MLME in response to a PLME-CCA.request primitive. The PLME-CCA.confirm primitive will return a status of either BUSY or IDLE, indicating a successful CCA, or an error code of TRX_OFF or TX_ON. The reasons for these status values are fully described in 6.2.2.1.3.

6.2.2.2.3 Effect on receipt

On receipt of the PLME-CCA.confirm primitive, the MLME is notified of the results of the CCA. If the CCA attempt was successful, the status parameter is set to either BUSY or IDLE. Otherwise, the status parameter will indicate the error.

6.2.2.3 PLME-GET.confirm

The PLME-GET.confirm primitive reports the results of an information request from the PHY PIB.

6.2.2.3.1 Semantics of the service primitive

The semantics of the PLME-GET.confirm primitive is as follows:

```
PLME-GET.confirm        (
                        status,
                        PIBAttribute,
                        PIBAttributeValue
                        )
```

Table 11 specifies the parameters for the PLME-GET.confirm primitive.

Table 11—PLME-GET.confirm parameters

Name	Type	Valid range	Description
Status	Enumeration	SUCCESS or UNSUPPORTED_ATTRIBUTE	The result of the request for PHY PIB attribute information.
PIBAttribute	Enumeration	See Table X	The identifier of the PHY PIB attribute to get.
PIBAttributeValue	Various	Attribute specific	The value of the indicated PHY PIB attribute to get.

6.2.2.3.2 When generated

The PLME-GET.confirm primitive is generated by the PLME and issued to its MLME in response to a PLME-GET.request primitive. The PLME-GET.confirm primitive will return a status of either SUCCESS, indicating that the request to read a PHY PIB attribute was successful, or an error code of UNSUPPORTED_ATTRIBUTE. The reasons for these status values are fully described in subclause 6.2.2.5.3.

6.2.2.3.3 Effect on receipt

On receipt of the PLME-GET.confirm primitive, the MLME is notified of the results of its request to read a PHY PIB attribute. If the request to read a PHY PIB attribute was successful, the status parameter is set to SUCCESS. Otherwise, the status parameter will indicate the error.

6.2.2.4 PLME-SET-TRX-STATE.request

The PLME-SET-TRX-STATE.request primitive requests that the PHY entity change the internal operating state of the transceiver. The transceiver will have three main states:

— Transceiver disabled (TRX_OFF).

— Transmitter enabled (TX_ON).

— Receiver enabled (RX_ON).

6.2.2.4.1 Semantics of the service primitive

The semantics of the PLME-SET-TRX-STATE.request primitive is as follows:

```
PLME-SET-TRX-STATE.request      (
                                state
                                )
```

Table 12 specifies the parameters for the PLME-SET-TRX-STATE.request primitive.

Table 12—PLME-SET-TRX-STATE.request parameters

Name	Type	Valid range	Description
state	Enumeration	RX_ON, TRX_OFF, FORCE_TRX_OFF, or TX_ON	The new state in which to configure the transceiver.

6.2.2.4.2 When generated

The PLME-SET-TRX-STATE.request primitive is generated by the MLME and issued to its PLME when the current operational state of the receiver needs to be changed.

6.2.2.4.3 Effect on receipt

On receipt of the PLME-SET-TRX-STATE.request primitive, the PLME will cause the PHY to change to the requested state. If the state change is accepted, the PHY will issue the PLME-SET-TRX-STATE.confirm primitive with a status of SUCCESS. If this primitive requests a state that the transceiver is already configured, the PHY will issue the PLME-SET-TRX-STATE.confirm primitive with a status indicating the current state, i.e., RX_ON, TRX_OFF, or TX_ON. If this primitive is issued with RX_ON or TRX_OFF argument and the PHY is busy transmitting a PPDU, the PHY will issue the PLME-SET-TRXSTATE.confirm primitive with a status BUSY_TX and defer the state change till the end of transmission. If this primitive is issued with TX_ON or TRX_OFF argument and the PHY is in RX_ON state and has already received a valid SFD, the PHY will issue the PLME-SET-TRX-STATE.confirm primitive with a status BUSY_RX and defer the state change till the end of reception of the PPDU. If this primitive is issued with FORCE_TRX_OFF, the PHY will cause the PHY to go the TRX_OFF state irrespective of the state the PHY is in.

6.2.2.5 PLME-SET-TRX-STATE.confirm

The PLME-SET-TRX-STATE.confirm primitive reports the result of a request to change the internal operating state of the transceiver.

6.2.2.5.1 Semantics of the service primitive

The semantics of the PLME-SET-TRX-STATE.confirm primitive is as follows:

```
PLME-SET-TRX-STATE.confirm        (
                                  status
                                  )
```

Table 13 specifies the parameters for the PLME-SET-TRX-STATE.confirm primitive.

Table 13—PLME-SET-TRX-STATE.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, RX_ON, TRX_OFF, TX_ON, BUSY_RX, or BUSY_TX	The result of the request to change the state of the transceiver.

6.2.2.5.2 When generated

The PLME-SET-TRX-STATE.confirm primitive is generated by the PLME and issued to its MLME after attempting to change the internal operating state of the transceiver.

6.2.2.5.3 Effect on receipt

On receipt of the PLME-SET-TRX-STATE.confirm primitive, the MLME is notified of the result of its request to change the internal operating state of the transceiver. A status value of SUCCESS indicates that the internal operating state of the transceiver was accepted. A status value of RX_ON, TRX_OFF, or TX_ON indicates that the transceiver is already in the requested internal operating state. A status value of BUSY_TX is issued when the PHY is requested to change its state to RX_ON or TRX_OFF while transmitting. A status value of BUSY_RX is issued when the PHY is in RX_ON state, has already received a valid SFD, and is requested to change its state to TX_ON or TRX_OFF.

6.2.2.6 PLME-SET.request

The PLME-SET.request primitive attempts to set the indicated PHY PIB attribute to the given value.

6.2.2.6.1 Semantics of the service primitive

The semantics of the PLME-SET.request primitive is as follows:

PLME-SET.request (

PIBAttribute

PIBAttributeValue

)

Table 14 specifies the parameters for the PLME-SET.request primitive.

Table 14—PLME-SET.request parameters

Name	Type	Valid range	Description
PIBAttribute	Enumeration	See Table X	The identifier of the PIB attribute to set.
PIBAttributeValue	Various	Attribute specific	The value of the indicated PIB attribute to set.

6.2.2.6.2 When generated

The PLME-SET.request primitive is generated by the MLME and issued to its PLME to write the indicated PHY PIB attribute.

6.2.2.6.3 Effect on receipt

On receipt of the PLME-SET.request primitive, the PLME will attempt to write the given value to the indicated PHY PIB attribute in its database. If the PIBAttribute parameter specifies an attribute that is not found in the database (see Table 19), the PLME will issue the PLME-SET.confirm primitive with a status of UNSUPPORTED_ATTRIBUTE. If the PIBAttibuteValue parameter specifies a value that is out of the valid range for the given attribute, the PLME will issue the PLME-SET.confirm primitive with a status of INVALID_PARAMETER.

If the requested PHY PIB attribute is successfully written, the PLME will issue the PLME-SET.confirm primitive with a status of SUCCESS.

6.2.2.6.4 PLME-SET.confirm

The PLME-SET.confirm primitive reports the results of the attempt to set a PIB attribute.

6.2.2.6.5 Semantics of the service primitive

The semantics of the PLME-SET.confirm primitive is as follows:

PLME-SET.confirm (

status,

PIBAttribute

)

Table 15 specifies the parameters for the PLME-SET.confirm primitive.

Table 15—PLME-SET.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, UNSUPPORTED_ATTRIBUTE, or INVALID_PARAMETER	The status of the attempt to set the requested PIB attribute.
PIBAttribute	Enumeration	See Table X	The identifier of the PIB attribute being confirmed.

6.2.2.6.6 When generated

The PLME-SET.confirm primitive is generated by the PLME and issued to its MLME in response to a PLME-SET.request primitive. The PLME-SET.confirm primitive will return a status of either SUCCESS, indicating that the requested value was written to the indicated PHY PIB attribute, or an error code of UNSUPPORTED_ATTRIBUTE or INVALID_PARAMETER. The reasons for these status values are fully described in subclause 6.2.2.9.3.

6.2.2.6.7 Effect on receipt

On receipt of the PLME-SET.confirm primitive, the MLME is notified of the result of its request to set the value of a PHY PIB attribute. If the requested value was written to the indicated PHY PIB attribute, the status parameter is set to SUCCESS. Otherwise, the status parameter will indicate the error.

6.2.2.7 PLME-DIMMER.request

The PLME-DIMMER.request primitive requests that the PLME perform the dimmer function as defined in 6.7.7.

6.2.2.7.1 Semantics of the service primitive

The semantics of the PLME-DIMMER.request primitive is as follows:

```
PLME-DIMMER.request          (
                             PIBDim
                             PIBDimValue
                             )
```

Table 14 specifies the parameters for the PLME-DIMMER.request primitive.

6.2.2.7.2 When generated

The PLME-DIMMER.request primitive is generated by the MLME and issued to its PLME whenever the dimmer algorithm requires the required dimming value.

Table 16—PLME-DIMMER.request parameters

Name	Type	Valid range	Description
PIBAttribute	Enumeration	See Table X	The identifier of the PIB attribute to set.
PIBAttributeValue	Various	Attribute specific	The value of the indicated PIB attribute to set.

6.2.2.7.3 Effect on receipt

If the transmitter is enabled on receipt of the PLME-DIMMER.request primitive, the PLME will cause the PHY to perform the required dimming function. When the PHY has completed the required dimming, the PLME will issue the PLME-DIMMER.confirm primitive with the status of COMPLETE.

6.2.2.8 PLME-DIMMER.confirm

The PLME-DIMMER.confirm primitive reports the results of a dimming request.

6.2.2.8.1 Semantics of the service primitive

The semantics of the PLME-DIMMER.confirm primitive is as follows:

```
PLME-DIMMER.confirm          (
                             status
                             )
```

Table 8 specifies the parameters for the PLME-DIMMER.confirm primitive.

Table 17—PLME-DIMMER.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	TRX_OFF, TX_ON, BUSY, or IDLE	The result of the request to perform a CCA.

6.2.2.8.2 When generated

The PLME-DIMMER.confirm primitive is generated by the PLME and issued to its MLME in response to a PLME-DIMMER.request primitive. The PLME-DIMMER.confirm primitive will return a status of either BUSY or IDLE, indicating a successful dimming. The reasons for these status values are fully described in 6.x.x.x.x.

6.2.2.8.3 Effect on receipt

On receipt of the PLME-DIMMER.confirm primitive, the MLME is notified of the results of the dimming. If the CCA attempt was successful, the status parameter is set to either BUSY or IDLE. Otherwise, the status parameter will indicate the error.

6.2.3 PHY enumerations description

Table 16 shows a description of the PHY enumeration values defined in the PHY specification.

Table 18—PHY enumerations description

Editor Note: these PHY enumerations have to be modified for VLC

Enumeration	Value	Description
BUSY	0x00	THe CCA attempt has detected a busy channel.
BUSY_RX	0x01	The transceiver is asked to change its state while receiving.
BUSY_TX	0x02	The transceiver is asked to change its state while transmitting.
FORCE_TRX_OFF	0x03	The transceiver is to be switched off.
IDLE	0x04	The CCA attempt has detected an idel channel.
INVALID_PARAMETER	0x05	A SET/GET request was issued with a parameter in the primitive that is out of the valid range.
RX_ON	0x06	The transceiver is in, or is to be configured into, the receiver enabled state.
SUCCESS	0x07	A SET/GET, an ED operation, or a transceiver state change was successful.
TRX_OFF	0x08	The transceiver is in, or is to be configured into, the transceiver disabled state.
TX_ON	0x09	The transceiver is in, or is to be configured into, the transmitter enabled state.
UNSUPPORTED_ATTRIBUTE	0x0a	A SET/GET request was issued with the identifier of an attribute that is not supported.

6.3 Data modes

The PHY shall support all the data transmission modes by the MAC.

"Single mode: There is only one PDU transferred per frame. Hence, this is used for very short data communication such as acknowledgements or association or beaconing or for vehicular broadcasting modes.

"Packed mode: The packed mode contains multiple PDUs per frame and is used to send multiple consecutive PDUs to the same destination within the frame for high throughput. Thus, the overhead of sending multiple MAC and PHY headers to the same destination is eliminated in this mode, providing higher MAC efficiency. This can be used in most modes as the preferred means of data communication.

"Burst mode: It is also possible for P2P types of communication to send long streams of data to the same destination even across frames. In such cases, a burst mode can be used that can reduce the preamble repetitions and the interframe spacing (IFS) between the consecutive frames. The reduced number of preambles improves the throughput of the system and eliminates the inefficiency of retraining the whole receiver since the previous frame was also sent to the receiver from the same transmitter. The Short Interframe Spacing (SIFS) between frames can also be reduced to Reduced Interframe Spacing (RIFS) since the next frame is also from the same source for the same destination. We provide the ability to reduce the number of preamble repetitions in this mode, allowing higher MAC efficiency.

6.4 PPDU format

This clause specifies the format of the PPDU packet.

For convenience, the PPDU packet structure is presented so that the leftmost field as written in this standard shall be transmitted or received first. All multiple octet fields shall be transmitted or received least significant octet first and each octet shall be transmitted or received least significant bit (LSB) first. The same transmission order should apply to data fields transferred between the PHY and MAC sublayer.

Each PPDU packet consists of the following basic components:

— A SHR, which allows a receiving device to synchronize and lock onto the bit stream.

— A PHR, which contains frame length information.

— A variable length payload, which carries the MAC sublayer frame.

6.4.1 General packet format

The PPDU packet structure shall be formatted as illustrated in Figure 16.

Table 19—Format of the PPDU

Octets: 4	**1**	**1**		**variable**	**TBD**
Preamble	SFD	Frame length (7 bits)	Reserved (1 bit)	PSDU	Frame Check Sequence
SHR		PHR		PHY payload	FCS

In the case of CCM, the following PPDU is used after link establishment.

Table 1

Octets: 4	1	TBD			Variable	TBD
Preamble	SFD	Frame length (7 bits)	Channel estimation Sequence (TBD)	Reserved (1 bit)	PSDU	Frame Check Sequence
SHR		PHR			PHY Payload	FCS

6.4.1.1 Preamble field

The preamble field is used by the transceiver to obtain chip and symbol synchronization with an incoming message. The preamble field is TBD. The standard defines one fast locking pattern followed by choice of 4 preambles for the purposes of distinguishing different PHY topologies.

The preamble first starts with a fast locking pattern of 64 alternate 1's and 0's. This maximum transition sequence provides the ability to lock the clock and data recovery circuit in the quickest time. Before the CDR attains lock and recovers the clock, it has no way of determining the logic value of the transmitted sequence. After the fast locking pattern, 4 repetitions of one of four preambles are sent.

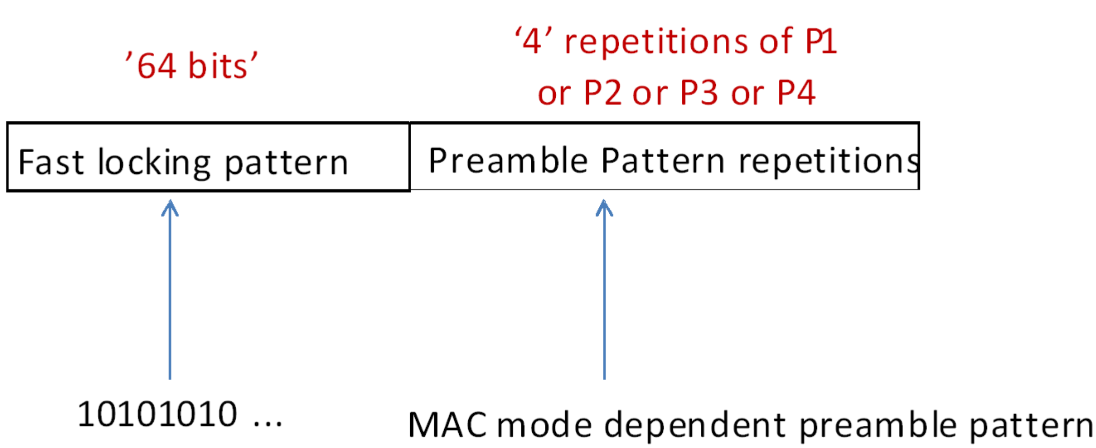


Figure 19—Default preamble transmission

P1:	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0
P2:	0	0	1	0	1	1	1	0	1	1	1	1	1	1	0
P3:	1	0	0	1	1	0	0	0	0	0	1	0	0	1	1
P4:	0	1	0	0	0	0	1	1	0	1	0	0	1	0	1

Figure 20—Proposed preambles for various topology modes

The preamble shall be transmitted using an OOK modulation. If there are multiple light sources supported by the device, all light sources shall transmit the same preamble simultaneously.

It is also acceptable to invert the proposed preamble sequences and transmit. The PHY can select whether to transmit each preamble sequence or its inversion. The advantage of doing this is that this allows two preamble sequences that can be searched simultaneously at the receiver for a given MAC operating mode and allow co-existence of two piconets in a given operating mode, without any increase in complexity.

Table 20—Preamble for MAC operation code

Preamble	Topology Operating Mode
P1 or inverted P1	topology independent
P2 or inverted P2	point to point
P3 or inverted P3	star
P4 or inverted P4	broadcast

The same preamble sequences are used for low rate and high rate PHY. The number of repetitions of the fast locking pattern can be extended by the MAC during idle time or for different operating modes for better synchronization or to provide visibility or image array device discovery.

P1 can be used with any topology and can also be used for visibility support frames.

6.4.1.2 Preamble for burst mode:

The fast locking pattern can be dropped for the burst mode since it is already synchronized to the transmitter. This reduces the preamble length by half and provides higher throughput at the MAC layer.

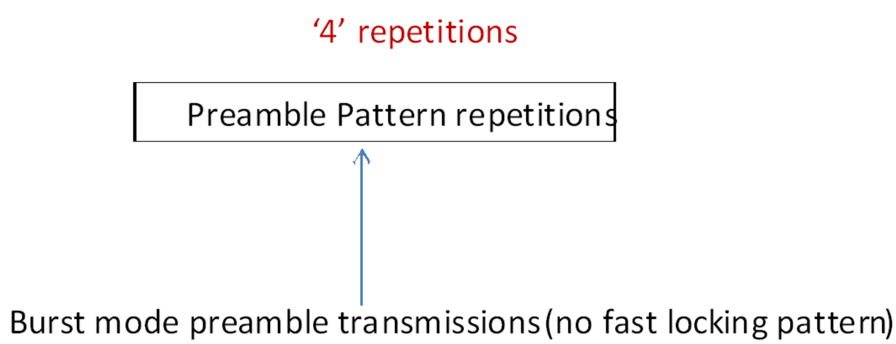


Figure 21—Burst preamble transmission

Figure 22—

6.4.1.3 SFD field

The SFD is an 8 bit field indicating the end of the synchronization (preamble) field and the start of the packet data. The SFD shall be formatted as illustrated in Figure 17.

The SFD is TBD.

6.4.1.4 Frame length field

The frame length field is 7 bits in length and specifies the total number of octets contained in the PSDU (i.e., PHY payload). It is a value between 0 and *aMaxPHYPacketSize* (see 6.x). Table 17 summarizes the type of payload versus the frame length value.

Table 21—Frame length values

Frame length values	Payload
0-4	Reserved
5	MPDU (Acknowledgment)
6-7	Reserved
8 to aMaxPHYPacketSize	MPDU

6.4.1.5 PSDU field

The PSDU field has a variable length and carries the data of the PHY packet. For all packet types of length five octets or greater than seven octets, the PSDU contains the MAC sublayer frame (i.e., MPDU).

6.4.1.6 HCS

The CRC calculation used for the header is a CRC-16 type CRC. The combination of PHY header and the MAC header shall be protected with a 2 octet CCITT CRC-16 header check sequence (HCS). The CCITT

CRC-16 HCS shall be the ones complement of the remainder generated by the modulo-2 division of the PHY header by the polynomial: x16 + x12 + x5 + 1. The HCS bits shall be processed in the transmit order. All HCS calculations shall be made prior to data scrambling. The registers shall be initialized to all ONEs.

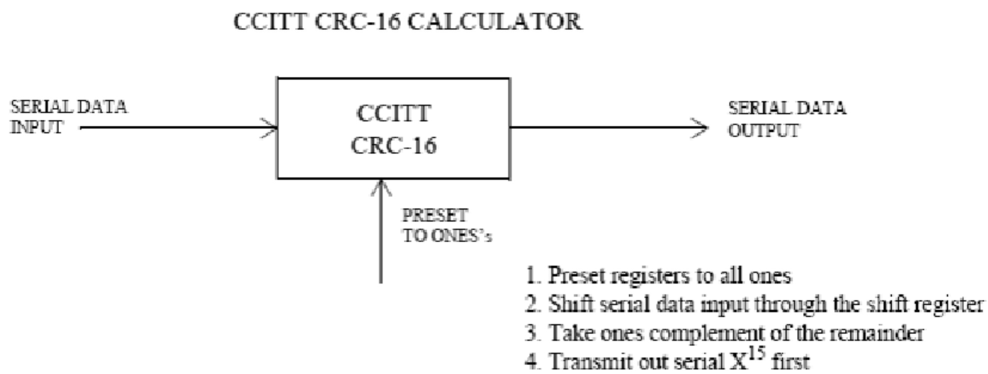
6.4.1.7 Frame Check Sequence

Ed. Note - is this done here or at the MAC level? If done at the MAC level then this clause should be removed.

The frame shall be protected with a CCITT CRC-16 frame check sequence (FCS). The CCITT CRC-16 HCS shall be the ones complement of the remainder generated by the modulo-2 division of the protected frame by the polynomial

x16+x12+x5+1

The protected bits shall be processed in transmit order. All HCS calculations shall be made prior to data scrambling. A schematic of the processing is shown in Figure X.



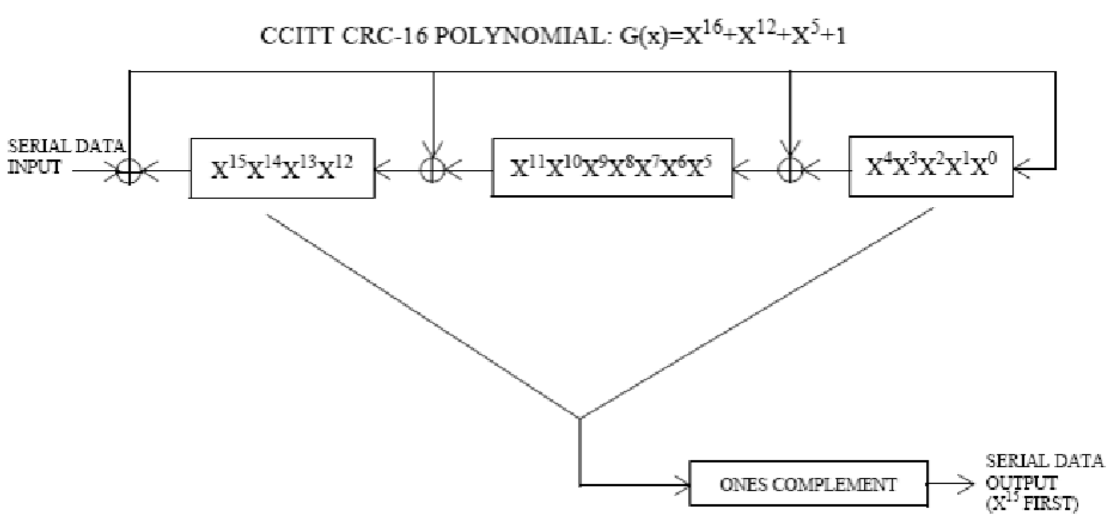


Figure 166—CCITT CRC-16 Implementation

As an example, consider the following 32-bit length sequence to be protected by the CRC-16

0101 0000 0000 0000 0000 0011 0000 0000

b0...b31

The leftmost bit (b0) is transmitted first in time.

The ones complement HCS for this sequence would be the following:

0101 1011 0101 0111

b0.............................b15

The leftmost bit (b0) is transmitted first in time. Bit b0 corresponds to X15 in the Figure 166.

An illustrative example of the CCITT CRC-16 HCS using the information from Figure 166 is shown in Figure X.

Data	CRC Registers msb lsb	
	1111111111111111	; Initialize preset to ones
0	1110111111011111	
1	1101111110111110	
0	1010111101011101	
1	0101111010111010	
0	1011110101110100	
0	0110101011001001	
0	1101010110010010	
0	1011101100000101	
0	0110011000101011	
0	1100110001010110	
0	1000100010001101	
0	0000000100111011	
0	0000001001110110	
0	0000010011101100	
0	0000100111011000	
0	0001001110110000	
0	0010011101100000	
0	0100111011000000	
0	1001110110000000	
0	0010101100100001	
0	0101011001000010	
0	1010110010000100	
1	0101100100001000	
1	1010001000110001	
0	0101010001000011	
0	1010100010000110	
0	0100000100101101	
0	1000001001011010	
0	0001010010010101	
0	0010100100101010	
0	0101001001010100	
0	1010010010101000	

Figure 167—Example of CRC calculation

The CRC-16 described in this subclause is the same one used in IEEE Std 802.11b™-1999 [B3].

6.4.2 PHY Header

The header shall be transmitted with an OOK modulation. If there are multiple light sources sup-ported by the device, all light sources shall transmit the same header contents simultaneously. The band plan ID field in this case shall be that of the lowest band plan ID.

Table 20—PHY Header

PHY header fields	Bit	Explanation on use
Burst mode	1	Reduce preamble and IFS (Inter Frame Spacing)
Channel number	3	Band plan ID
Data rate	5	PHY data rate
Length of MAC payload	16	Length up to 64KB
Alternate Mode	1	CCM
Reserved fields	6	Future use

6.5 PHY constants and PIB attributes

This subclause specifies the constants and attributes required by the PHY.

6.5.1 PHY constants

The constants that define the characteristics of the PHY are presented in Table 18. These constants are hardware dependent and cannot be changed during operation.

6.5.2 PHY PIB attributes

The PHY PIB comprises the attributes required to manage the PHY of a device. Each of these attributes can be read or written using the PLME-GET.request and PLME-SET.request primitives, respectively. The attributes contained in the PHY PIB are presented in Table 19.

Table 22—PHY constants

Constant	Description	Value
aMaxPHYPacketSize	The maximum PSDU size (in octets) the PHY shall be able to receive.	127
aTurnaroundTime	RX-to-TX or TX-to-RX maximum turn-around time (see 6.x.x and 6.x.x)	12 symbol periods

Table 23—PHY PIB attributes

Attribute	Identifier	Type	Range	Description
phyCurrentChannel	0x00	Integer	0-26	The RF channel to use for all following transmissions and receptions (see 6.x.x).
phyChannelsSup-ported	0x01	Bitmap	See descrip-tion	The 5 most significant bits (MSBs) (b27,... , b31) of phyChannelsSupported shall be reserved and set to 0, and the 27 LSBs (b0, b1, ... b26) shall indicate the status (1=available, 0=unavailable) for each of the 27 valid channels (bk shall indicate the status of channel k as in 6.1.2).
phyCCAMode	0x02	Integer	1-3	The CCA mode (see 6.x.x)

6.6 PHY Specifications

6.6.1 PHY TYPE 1 specifications

The type 1 PHY is targetted towards applications requiring data rates operating at several tens of meters of range with data rates shown in Table X.

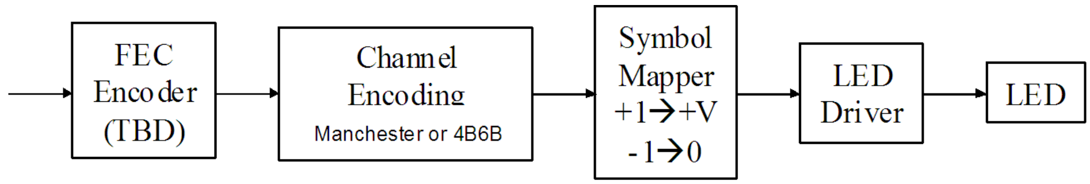
6.6.1.1 Data rate

The LRP supports data rates of 25 kbps, 50 kbps and 100 kbps using OOK and 200 kbps and 400 kbps using VPM. The data rate of 25 kbps is used for link establishment. After the link is established other data rates may be utilized based upon the desired quality of service.

6.6.1.1.1 Reference modulator diagram

A reference implementation is shown below.

Note: Figure may need to be updated to remove reference to LED and particular choice for channel encod-ing.



6.6.1.1.2 Bit-to-symbol mapping for Manchester coding

A bit value of logic high shall be manchester encoded as a logic high followed by a logic low. A bit value of logic low shall be manchester encoded as a logic low followed by a logic high.

6.6.1.1.3 Optical symbol mapping

A logic level high applied to the light source shall result in a high radiated intensity. A logic level low applied to the light source shall result in a reduced radiated intensity.

6.6.2 PHY Type 2 specifications

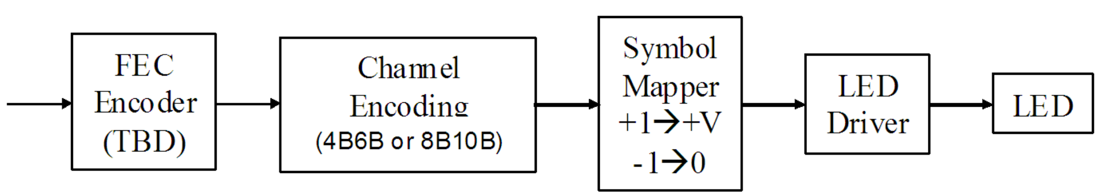
The type 2 PHY is targetted towards applications requiring high data rates operating at several meters of range with data rates shown in Table X.

6.6.2.1 Data rate

This PHY supports data rates of 3.2 Mbps and 6.4 Mbps using VPM modulation and data rates of 9.6 Mbps, 24 Mbps, 38.4 Mbps, 76.8 Mbps and 96 Mbps using OOK modulation. The VPM data rate of 6 Mbps is used for link establishment (Ed. Note: what duty cycle is used for link establishment? 50%?). After the link is established other data rates may be utilized based upon the desired quality of service.

6.6.2.1.1 Reference modulator diagram

A reference implementation is shown below.



6.6.2.1.2 Optical symbol mapping

A logic level high applied to the light source shall result in a high radiated intensity. A logic level low applied to the light source shall result in a reduced radiated intensity.

6.6.2.2 Frame Flicker Compensation (Ed. Note: this is an optional approach)

To prevent the LED from appearing "dimmer" during the packet frame transmission time, an idle pattern is sent between frames that has the same duty cycle as the modulated frame but the pulse repetition rate (exact repetition rate is TBD) is set much lower so as not to cause "in band" interference with any VLC modulation.

6.6.2.2.1 Filler Bit Pattern (Ed. Note: optional)

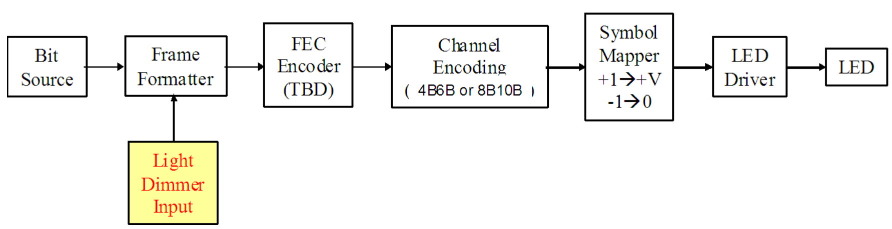
The bit pattern used for the filler sequence shall be a repetitive 1010. The ratio of ones and zeros shall be adjusted so as to make the required dimming as per clause X.X.X. The number of bits in the fillter pattern shall be an even number so as to maintain a DC balance on this sequence. The extinction ratio used for the transmission of the filler sequence shall be the same used for actual data packets.

6.6.2.2.2 Filler Bit Rate

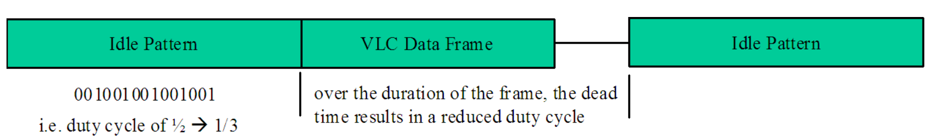
The filler sequence shall be sent with a bit rate that is approximately TBD bps.

6.6.2.3 Lighting Dimming (Ed. Note: Is this what is used for VPM and CCM?)

Light dimming is generally a MAC layer function; however, it does require that the PHY periodically turn off the light source. The details are shown in clause 7.X.X



OFF time is inserted into either the idle pattern or into the data frame, as shown below, to reduce the average intensity of the light.



6.6.2.3.1 Idle Pattern Extinction Ratio

The extinction ratio ideally should be 100% but practically it can be as large as possible.

(Ed. Note: based upon the discussion from 09-0795-00 from Doug, the above statement is probably not true!)

6.6.3 High data rate and CCM PHY specifications (Ed. Note: this needs to be broken out for Type 2 support and CCM support)

The standard shall support both low and high data rates for supporting multiple applications. The low and high data rates of the IEEE 802.15.7 PHY shall be from 3.2 Mbps to 96Mbps in uncoded data rate as shown in Table X.

6.6.3.1 DC Balancing Code

Target application of PHY for VLC is the communication using an illumination at office or home environments. The target light source for VLC is white LED with yellow phosphor and RGB LED. The data rate and range for illumination is over 1Mbps and the distance range is in 3 meter. The divergence angle of LED illumination is very various. LED fluorescent has 110 degree to 310 degree. PAR type has 60 to 140 degree. PAR type is similar to halogen lamp. 3 meter is a general distance between light on the ceiling and on the table at office or home.

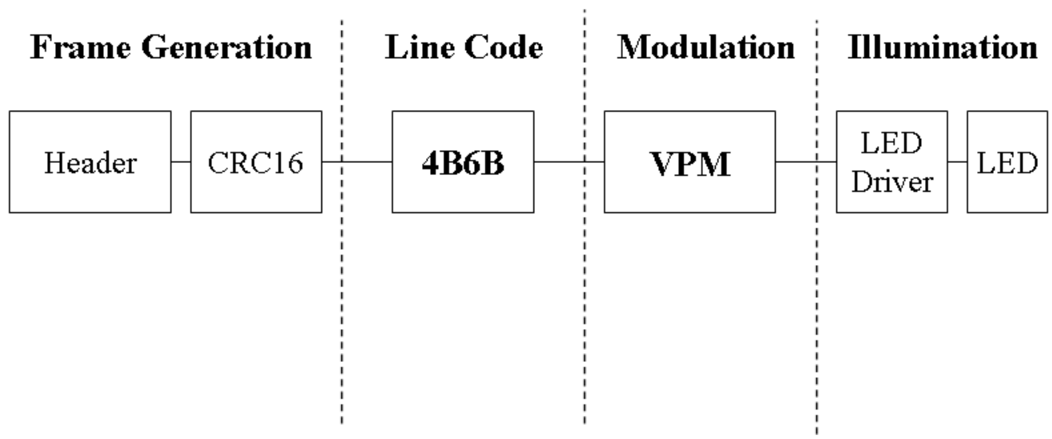


Figure 23—PHY models for dimmable and non-flickering illumination

(Informative) Flickering of illumination is a harmful for human eyes. Some modulations make a flickering. Flickering defines an unexpected and unpredictable light intensity change recognized by human eyes. The flickering causes from a repetition of lighting on and off or slow change of brightness in a time period. There is a flickering in VLC lower data rate than 200 bps. Human eye can recognize the light status of on or off from light source. Some data pattern like long sequence of 1 or 0 produce off time and on time repeatedly.

0000 0001 0101 0111 1111 1110 1010 1000 0000

Maximum Flickering Time Period (MFTP) is a period that light intensity can be changed, but that cannot be recognized the change of brightness by human eyes;

MFTP: 1/minimum flickering free frequency (200Hz) = 5ms

To avoid a flickering from VLC, a brightness of each MFTP must be all equal. There are needed a flickering definition and MFTF (Max Flickering Time Period) by VLC or human eye safety regulation.

A solution for flickering removal is that we make a ratio of positive and negative level per MFTP to be constant with constant-weight code such as Manchester code, 2 PPM, and 4PPM. Manchester code has 50% duty cycle always. 2 PPM is 50% and 4 PPM is 25%. If we use this line code or modulation scheme for data stream and at idle time we use same waveform, flickering will not occur. But if we use NRZ OOK, we need another solution. Second solution is we make a ratio of 1 and 0 per MFTP to be constant at data stream.

VLC PHY Line code can use 4B6B and 8B10B. VLC PHY modulation supports On/off Keying and Variable Pulse Position Modulation (VPM). PHY supports also Time Division Multiplexing(TDM) for LED signboard.

6.6.3.1.1 Code 4B6B

4B6B expands 4-bit codes to 6-bit symbols with same ratio of 1 and 0 (3:3) and 50% duty cycle.

Features of 4B6B are always 50% duty cycle, reduced run length 8 to 4, and error detection. 4B6B can detect error by number of 1 and 0, but cannot detect the position change of 1 and 0:

0: 001110 ? 001101 : 1

4B6B supports clock recovery and DC-balanced waveform.

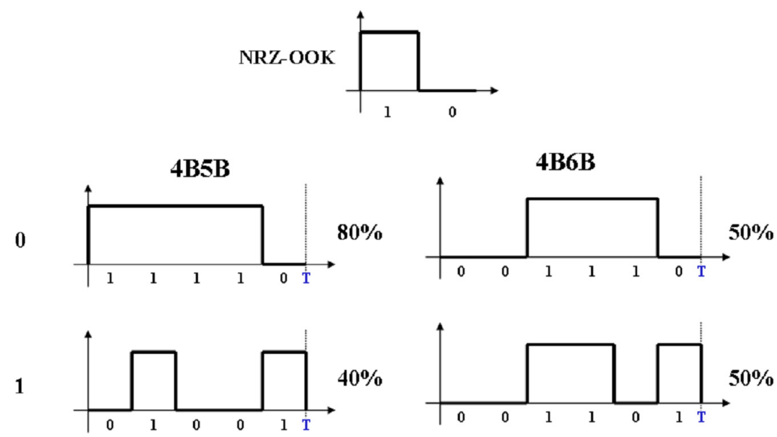


Figure 24—An example of 4B5B and 4B6B at NRZ OOK (Ed. Note: need to remove the 4B5B example for this figure)

6.6.3.1.2 8b10b line coding

The 8B/10B line code that converts 8-bit to 10-bit is also proposed. It can help to acquire DC-balance, disparity, and clock recovery by enough state changes. It is specified in ANSI/INCITS 373: Fiber Channel Framing and Signaling Interface (FC-FS), Clause 11

Features

- DC balanced line code
- Combination of 3B4B and 5B6B encoding
- Error detection capability
- Run length is limited to 5.
- Disparities are constrained to be -2, 0, 2.

- 3B4B encoding (bottom)

- 5B6B encoding (right)

Table 24—Example of line coding

	(RD-)	D20.7	(RD+)	D7.1	(RD+)
olation	(RD-)	001011 0111	(RD+)	111000 1001	(RD+)
rrect	(RD-)	001011 0111	(RD+)	000111 1001	(RD+)

6.6.3.2 Modulation

Several modulation methods are used in high data rate PHY. CCM (Color Code Modulation), OOK(On Off Keying) and V-PPM(Variable PPM) are example.

LED office illumination can support a wireless communication such as LED illumination infrastructure to mobile. The LEDs for transmission device are two types: white LED (yellow phosphor) and R-G-B LED. A white LED (yellow phosphor) is more popular than R-G-B LED due to the price. A white LED(yellow phosphor) has less communication quality than R-G-B LED due to the response time of phosphor materials. Data rate is 1Mbps(DL/UL) at distance 3 m. VLC can be support all kind of direction such as bi-direction (full or half) and uni-direction.

6.6.3.2.1 OOK

We define OOK as the basic mode of communication. OOK is used for the preamble and header. Beacons and other device discovery, link establishment messages are sent in this mode. This mode does not require knowledge of transmitter or receiver characteristics.

6.6.3.2.2 CCM (Color Code Modulation)

CCM (Color Code Modulation) is a new modulation scheme proposed for the standard. CCM assumes VLC systems which consist of multi color light sources and photo detectors, which is same as WDM. Although WDM is one of the methods for high speed data transmission, CCM has some advantages over WDM (Multi color OOK).

1) Connectivity is guaranteed by the color coordinates

CCM channels are decided by mixed colors that are allocated in the color coordinates plane. Therefore, the connectivity is guaranteed by the color constellation on the xy color coordinates.

2) Total power is constant

In CCM concept, the total power of all light sources is constant; therefore, the envelope of the sum of all light signals is constant.

3) Variable bit rate

In OOK case, the raw bit rate (code rate=1) is decided by just the symbol rate. That means OOK bit rate limited by the frequency response of the LED.

In CCM case, the raw bit rate is decided by the symbol rate and the number of color points on the constellation. That means CCM bit rate is not limited by the frequency response of the LEDs.

6.6.3.2.3 CCM principle

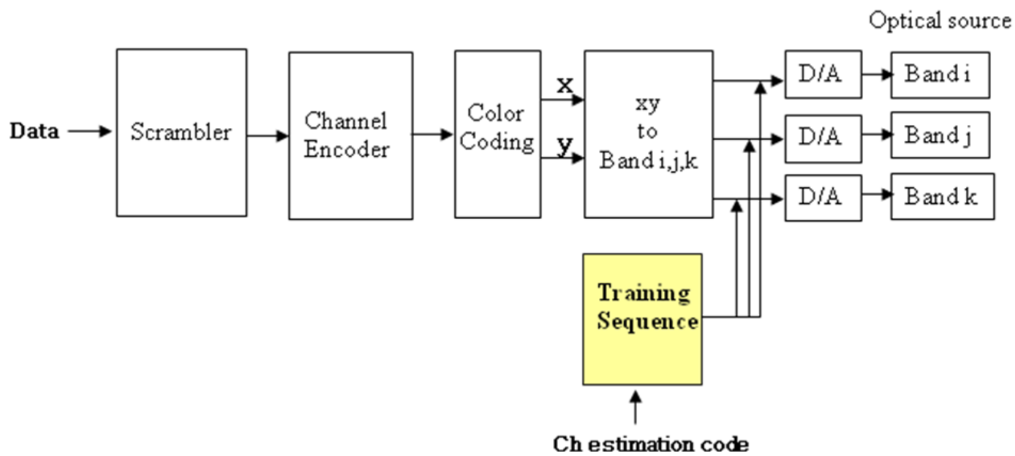


Figure 25—CCM system

Figure 25 shows the CCM system configuration, in case of 3 colors VLC system could have some degradationlight devices.

In that figure, transmit data is coded by the color coding block into xy values according to the xy color coordinates.

Figure 32 shows the CIE1931 xy color coordinate with the example for CCM symbol positions (constellation) in 4 point CCM (4CCM) case. In this case, 4 Symbol points are placed in the RGB tri angle. That means this system can send 2 bits data information per symbol.

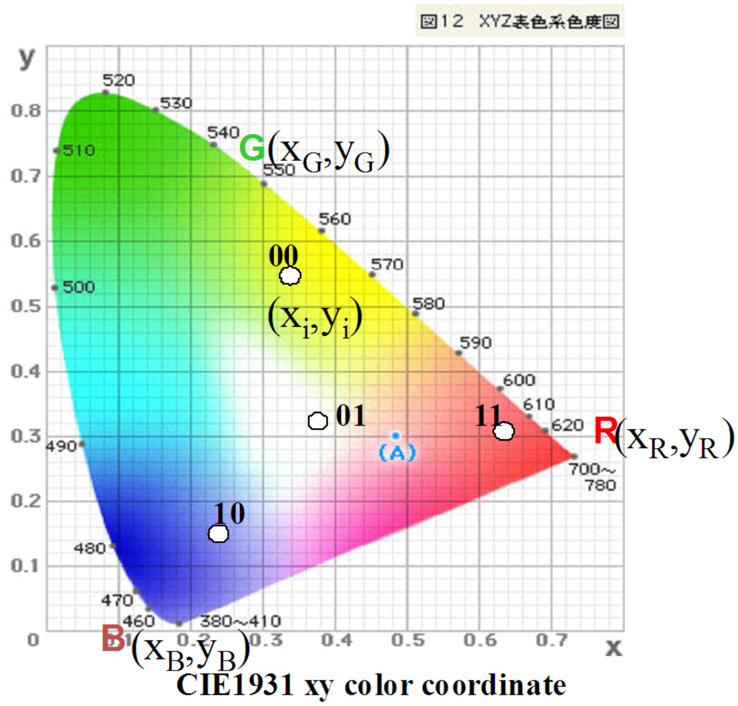


Figure 26—CIE1931 xy color coordinate

All visible colors in the color palette defined by xy values. (xR,yR), (xG,yG), (xB,yB) shows the xy coordinates of the actual RGB LED devices. And (xi,yi) shows the one of the allocated color point in 4CCM.

The color point (xi,yi) is generated by 3 LEDs' intensity R, G and B in figure 32. These xy values are transformed into RGB values.

The relation between (xR,yR), (xG,yG), (xB,yB) , (xi,yi) and RGB is showed by following simultaneous equations.

$$x_i = R \cdot x_R + G \cdot x_G + B \cdot x_B$$
$$y_i = R \cdot y_R + G \cdot y_G + B \cdot y_B$$
$$R + G + B = 1$$

In those equations, R, G and B show the normalized intensity of each LED.

In the receiver side, xy values are calculated from received RGB values. And xy values are decoded into the received data.

In this system, CCM symbols are provided as the visible colors which are made by RGB light sources.

And, the information is transmitted as the intensity ratio among RGB. Not as the each RGB absolute val-ues like WDM.

6.6.3.2.4 Color constellation for CCM

Figure 32a shows the proposed color constellation for the CCM.

4CCM can send 2bits per symbol. 8CCM can send 3bits per symbol. 16CCM can send 4bits per symbol.

Those color constellations were decided for having same and max distance from adjacent symbols.

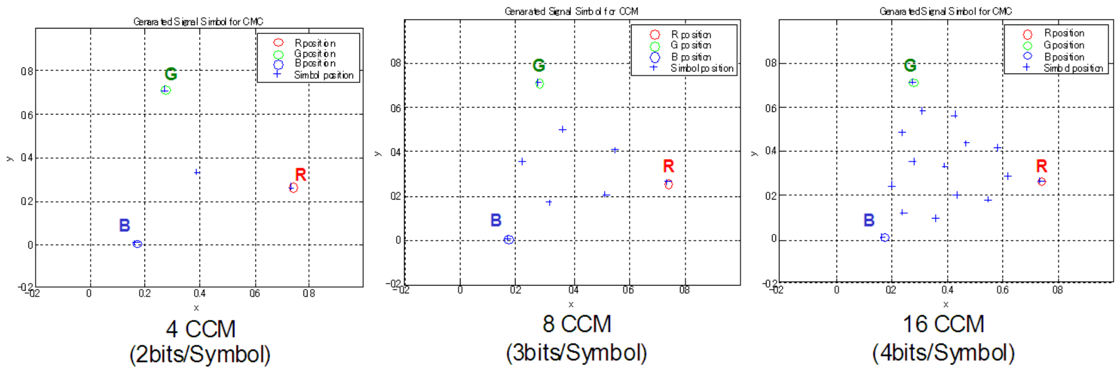


Figure 27—Color constellations for CCM

6.6.3.2.5 Data rate specification for CCM

Data rate of CCM is decided by the symbol rate and the number of color points in the constellation that means CCM mode (4/8/16CCM).

Table 26 shows the proposed data rate for CCM mode.

Optical Rate	CCM mode	FEC	Bit rate
12MHz	4CCM	1/2	12Mbps
12MHz	8CCM	1/2	18Mbps
24MHz	4CCM	1/2	24Mbps
24MHz	8CCM	1/2	36Mbps
24MHz	16CCM	1/2	48Mbps
24MHz	8CCM	1	72Mbps
24MHz	16CCM	1	96Mbps

Table 25—Proposed data rate for CCM mode

6.6.3.2.6 CCM Calibration

VLC system could have some degradation, for example, multi-color imbalance, multi-color interference or other error on xy color coordinates caused by ambient light or own light device characteristics. Therefore, we have to prepare CCM compensation method.

CCM calibration is proposed for solving the problem.

In figure 31, the system estimates the channel propagation matrix using orthogonal sequence (ex. Walsh code) included in the header of the frame.

Data symbols are compensated by using the estimated channel matrix. It is similar as MIMO algorithm on radio systems.

6.6.3.2.7 CCM Dimming

In CCM, total power of multiple light sources is constant. For dimming control, the total power of the multiple light sources is changed. CCM keeps the center color of the color constellation with required intensity instead of the idle pattern shown in clause 6.6.2.3.

6.6.3.2.8 Variable PPM (Ed. Note: Much of this material is informrative - move to the Annex)

There are main three factors that are non-flickering, dimming control, and full brightness in VLC modulation scheme for illumination.

A flicker LED light due to VLC modulation is not good for eye safety. We need a modulation to remove the flicker for eye safety. If we cannot remove the flicker in VLC for illumination, no one use a VLC as an illumination.

LED illumination can control brightness with a dimming scheme. The dimming function is a mandatory for LED illumination. There are needed a modulation to support the dimming control function of LED light for VLC and illumination.

Full brightness is a primary function of LED illumination. A modulation of VLC might be decrease the brightness of LED illumination. There are needed a modulation to support full brightness in terms of illumination. It is desirable that VLC for illumination achieve the full brightness as much as LED light only for illumination do.

There are several candidates of VLC modulation as well as LED illumination. We can consider the modulation such as NRZ - OOK, RZ - OOK, PPM, I-PPM, PWM, and VPM.

NRZ-OOK(Non Return to Zero - On Off Keying) is one of the simple modulation scheme and a kind of amplitude-shift keying (ASK) modulation that represents digital data of "1" or "0" as the "on" or "off" states with non return to zero on off keying. Without line code, the flicker may be appeared. It is also difficult to achieve the dimming control and full brightness.

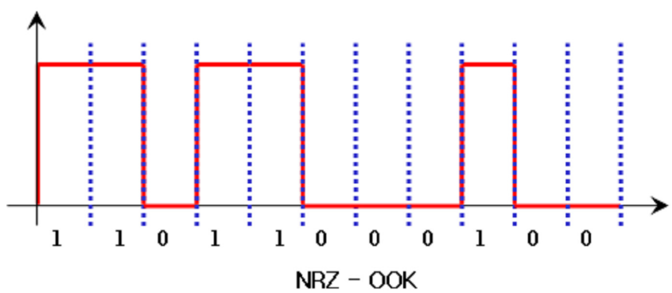


Figure 28—An example of NRZ - OOK

RZ-OOK(Return to Zero - On Off Keying) is one of the simple modulation scheme and a kind of amplitude-shift keying (ASK) modulation that represents digital data of "1" or "0" as the "on" or "off" states with return to zero on off keying.. Without line code, the flicker may be appeared. It is also difficult to achieve the dimming control and full brightness.

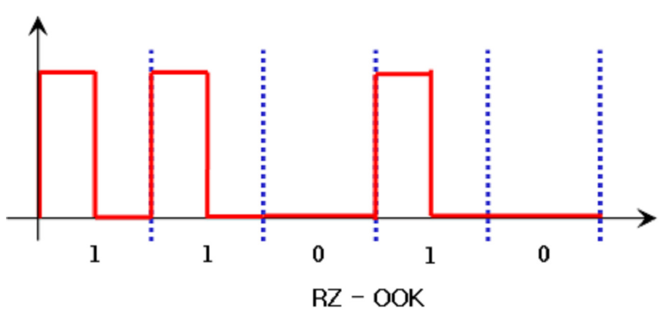


Figure 29—An example of RZ-OOK

PPM (Pulse Position Modulation) is that M message bits are encoded by transmitting a single pulse in one of 2M possible time-shifts. PPM is a good modulation for the non-flickering. But, it is difficult to achieve the dimming control and full brightness.

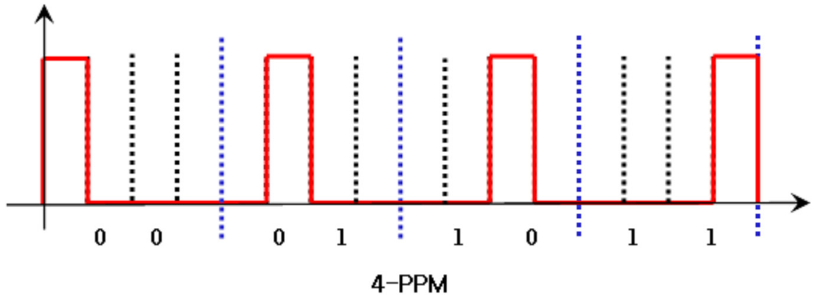


Figure 30—An example of PPM (Pulse Position Modulation)

I - PPM (Inverse - PPM) is that M message bits are encoded by transmitting a single pulse in one of 2M possible time-shifts. I-PPM is a good modulation for the non-flickering and the full brightness. But it is difficult to achieve the dimming control.

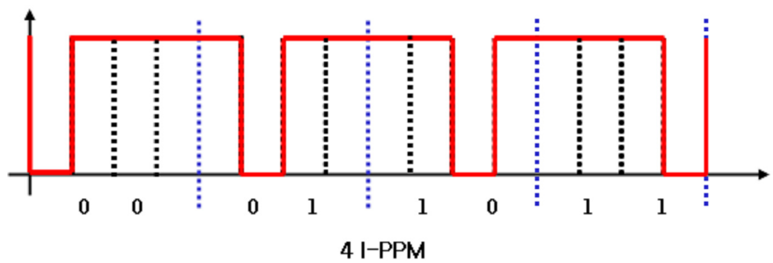


Figure 31—An example of I-PPM (Inverse Pulse Position Modulation)

PWM (Pulse Width Modulation) is the modulation scheme widely used in LED illumination for itself. So, we can basically achieve the flicker-free, the dimming control, and the full brightness by using PWM. If we use PWM only itself for VLC, we cannot obtain the flickering-free, the dimming control, or the full brightness.

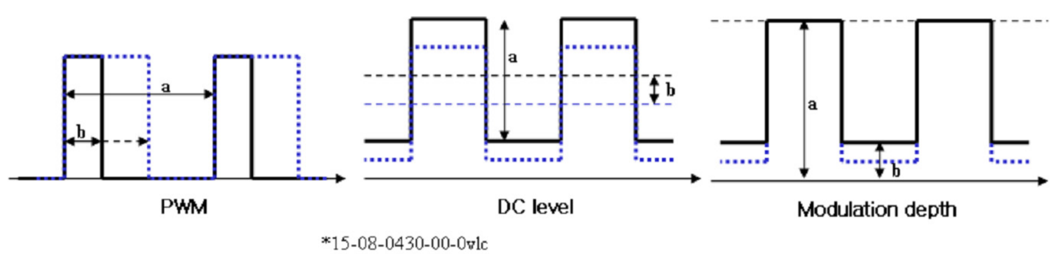


Figure 32—An example of PWM (Pulse Width Modulation)

VPM (Variable PPM) provides three main functions of illumination: non-flickering, dimming control, and full brightness. The basic concept of VPM is a combination of PWM and 2-PPM. 2-PPM(Pulse Position Modulation) provides a function without flickering. PWM (Pulse Width Modulation) provides a brightness control using duty cycle control. VPM equals to 2-PPM when the duty of VPM is 50 %.

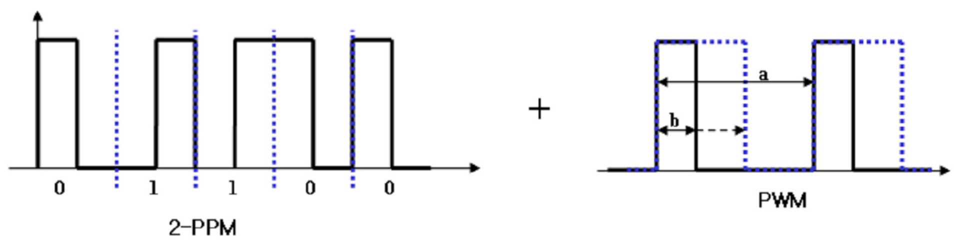


Figure 33—The basic concept of Variable PPM

We make an example waveform of proposed VPM with 75 % duty cycle. As you can see, In VPM, the flicker is free because the "on" state area is constant (same ratio) during each time period.

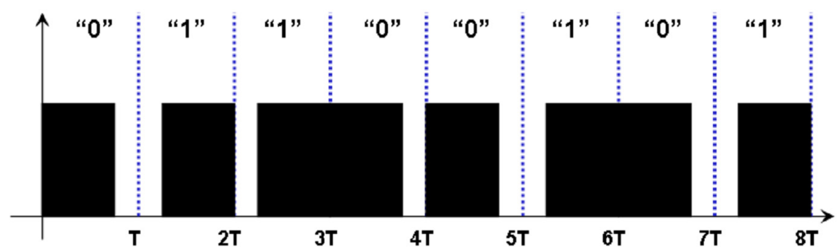


Figure 34—Example Waveform of Proposed VPM with 75% duty

We can make the VPM waveforms showing dimming control according to duty cycle. VPM provides the dimming control by adjusting the duty and the full brightness by increase of duty cycle resolution.

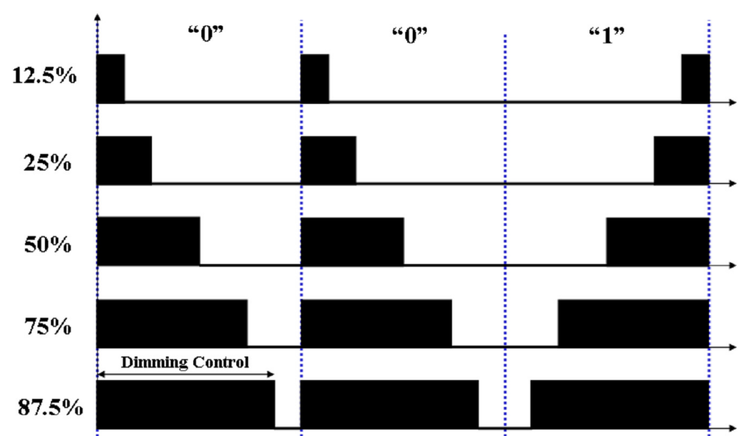


Figure 35—An example of Dimming Control by VPM Signal

VPM provides both functions of illumination and communications with non-flickering, dimming control, and full brightness. VPM does not need a line code scheme for flicker-free signal. VPM is that the "on" state area of LED light is always constant under the given duty cycle. The dimming control of VPM can be provided by the duty cycle adjustment. The full brightness of VPM can be provided by the increase of the duty cycle resolution.

6.6.3.3 VPM Dimming

The VPM PHY will have basic dimming level support at 10% duty cycle resolution (note: for ease of implementation). To support higher resolution for dimming, the VPM PHY shall use the same algorithm as that mentioned for the in-band visibility pattern mentioned below. For example, for supporting 25% dimming, the VPM PHY shall alternately send 20% and 30% duty cycle symbols.

•Dimming or visibility levels : $V_0, V_1, \ldots, V_K$ ($V_0 = 0\%, V_K = 100\%$)

• Desired visibility for dimming = dv (percentage)

• Desired precision = $p, p \le 0, p \in Z$

Algorithm:

$$\text{sel1pat} = \left\lfloor \frac{dv * K}{100} \right\rfloor$$

$$\text{sel2pat} = \left\lceil \frac{dv * K}{100} \right\rceil$$

$$\text{reppat2} = 10^{-p}\left(dv - \frac{100 * \text{sel1pat}}{K} \right)$$

$$\text{reppat1} = 10^{1-p} - \text{reppat2}$$

repeat V_{sel1pat} reppat1 times

repeat V_{sel2pat} reppat2 times

6.6.3.4 Channel Coding

A Reed-Solomon code is proposed (255, k) to correct errors made by any line codes and to increase robustness of the system. The Reed-Solomon code may be shorted for the last block if it does not meet the block size requirements. No zero padding is required for the RS code.

The Reed Solomon code proposed is a systematic RS code. The Reed-Solomon code is defined over GF(28) with a primitive polynomial p(z) = z8 + z4 + z3 + z2 + 1, where ? is the root of the polynomial p(z). For brevity, this Galois field is denoted as F. As notation, the element M = b7z7 + b6z6 + b5z5 + b4z4 + b3z3 + b2z2 + b1z + b0, where M ? F, has the following binary representation b7b6b5b4b3b2b1b0, where b7 is the MSB and b0 is the LSB

The generator polynomial is obtained by shortening a systematic (255, k) Reed-Solomon code, which is specified by the generator polynomial

g(x) = (x ? ?i) = x6 + 126x5 + 4x4 + 158x3 + 58x2 + 49x + 117, where g(x) is the generator polynomial over F, x ? F and the coefficients are given in decimal notation.

Shortening operation:

"Start by (255, k) RS code, one can get an (255-s, k-s) shortened RS code as follows:

"Pad the k-s symbols with s zero symbols.

"Encode using (255, k) RS encoder.

"Delete the padded zeros (don't transmit them).

"At the decoder, add the zeros, then decode.

Note: the minimum distance of the (255-s, k-s) RS code is the same as the minimum distance of the (n, k) RS code. So, still can correct (n-k)/2 errors.

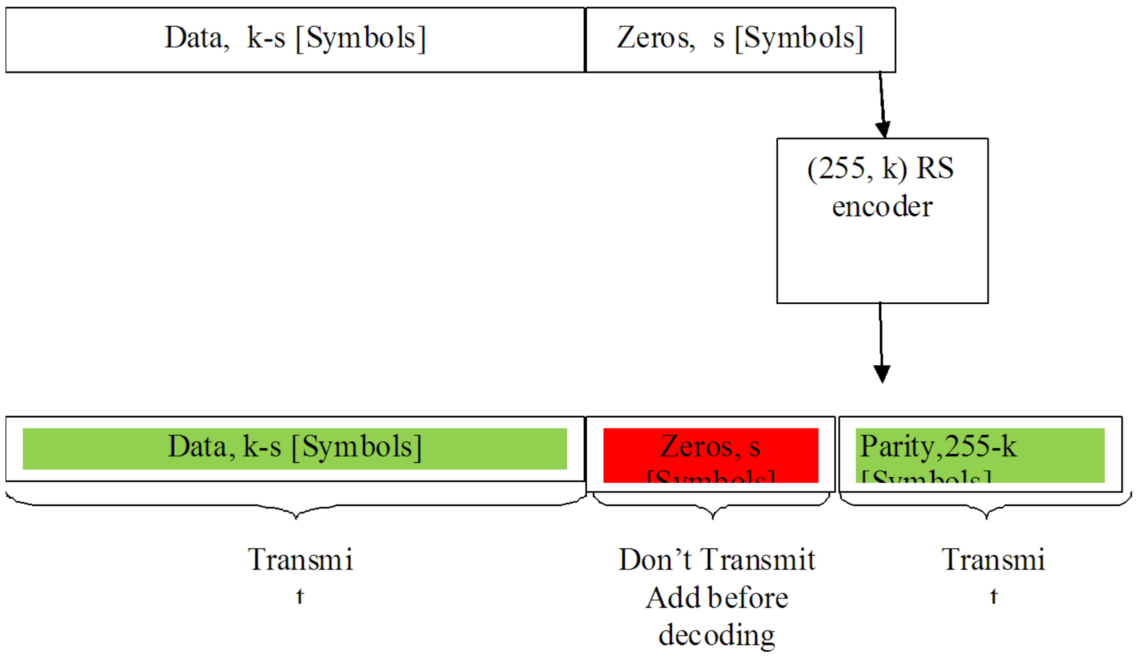


Figure 36—Shortened RS code generation

6.6.4 Color Quality Indicator support

A device shall be capable of estimating the link quality of the received color channel, where the color quality shall be defined as an estimate of the SNR available after the CDR and will include all implementation losses associated with that particular receiver architecture (quantization noise, channel estimation errors, etc.). All estimated values, when measured under static channel conditions, shall be monotonically increasing with signal strength over the entire reporting range. Note that the estimates may exhibit saturation behavior at values higher than that required for highest data rate operation. Finally, the link quality estimates shall be made on a packet-by-packet basis. No bounds on absolute accuracy with respect to an external reference plane are intended or implied by this specification.

6.7 General radio specifications

The specifications in 6.7.1 through 6.7.9 apply to the PHY TYPES 1 and 2.

6.7.1 TX-to-RX turnaround time

The TX-to-RX turnaround time shall be less than *aTurnaroundTime* (see 6.4.1).

The TX-to-RX turnaround time shall be measured at the air interface from the trailing edge of the last transmitted symbol until the receiver is ready to begin the reception of the next PHY packet.

6.7.2 RX-to-TX turnaround time

The RX-to-TX turnaround time shall be less than aTurnaroundTime (see 6.4.1).

The RX-to-TX turnaround time shall be measured at the air interface from the trailing edge of the last chip (of the last symbol) of a received packet until the transmitter is ready to begin transmission of the resulting acknowledgment. Actual transmission start times are specified by the MAC sublayer (see 7.5.6.4.2).

6.7.3 Error-vector magnitude (EVM) definition

The modulation accuracy of an IEEE 802.15.7 transmitter is determined with an EVM measurement. In order to calculate the EVM measurement, a time record of N received complex chip values is captured. For each received chip, a decision is made about which chip value was transmitted. The ideal position of the chosen chip (the center of the decision box) is represented by the vector . The error vector is defined as the distance from this ideal position to the actual position of the received point (see Figure 22).

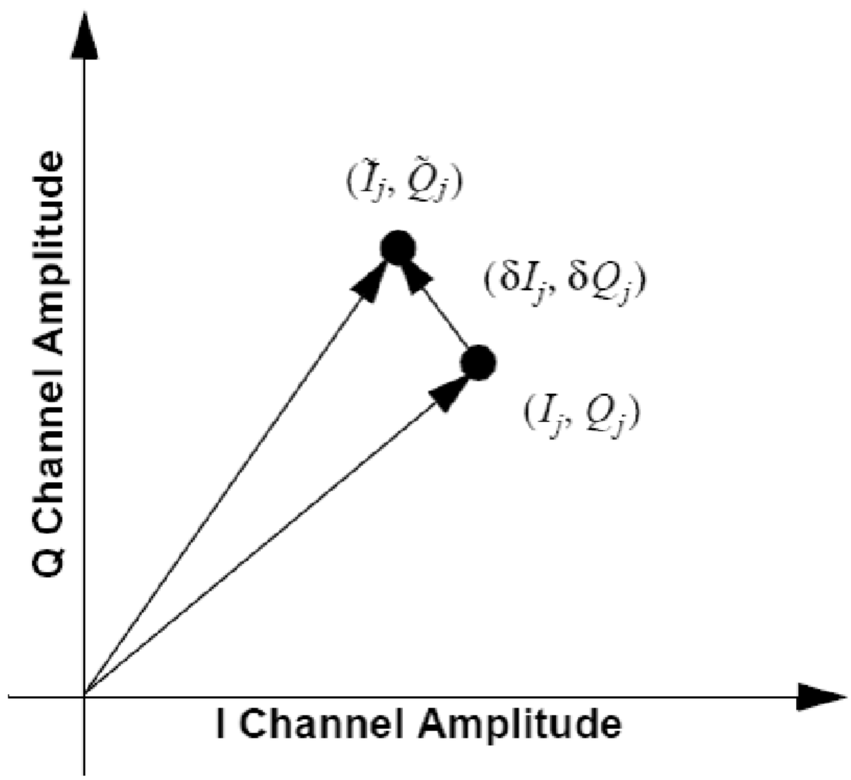


Figure 22—Error vector calculation

NEED TO FINISH THIS SECTION - WE SHOULD SPECIFY AN ERROR VECTOR MAGNITUDE FOR OOK/VPM. ARE WE GOING TO DO THIS FOR CCM?

6.7.3.1 EVM calculated values

An IEEE 802.15.7 transmitter shall have EVM values of less than TBD% when measured for 1000 chips. The error-vector measurement shall be made on baseband I and Q chips after recovery through a reference receiver system. The reference receiver shall perform carrier lock, symbol timing recovery, and amplitude adjustment while making the measurements.

6.7.4 Transmit frequency tolerance

The transmitted frequency tolerance shall be ± TBD ppm maximum.

6.7.5 LQI

The LQI measurement is a characterization of the strength and/or quality of a received packet. The measurement may be implemented using receiver ED, a signal-to-noise ratio estimation, or a combination of these methods. The use of the LQI result by the network or application layers is not specified in this standard.

The LQI measurement shall be performed for each received packet, and the result shall be reported to the MAC sublayer using PD-DATA.indication (see 6.2.1.3) as an integer ranging from 0x00 to 0xff. The minimum and maximum LQI values (0x00 and 0xff) should be associated with the lowest and highest quality IEEE 802.15.7 signals detectable by the receiver, and LQ values in between should be uniformly distributed between these two limits. At least eight unique values of LQ shall be used.

6.7.6 CCA

The IEEE 802.15.4 PHY may provide the capability to perform CCA according to at least one of the following three methods:

— CCA Mode 1: Energy above threshold. CCA may report a busy medium upon detecting any energy above the energy detect threshold.

— CCA Mode 2: Carrier sense only. CCA may report a busy medium only upon the detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4. This signal may be above or below the energy detect threshold.

— CCA Mode 3: Carrier sense with energy above threshold. CCA may report a busy medium only upon the detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4 with energy above the energy detect threshold.

For any of the CCA modes, if the PLME-CCA.request primitive (see 6.X.X.X) is received by the PHY during reception of a PPDU, CCA may report a busy medium. PPDU reception is considered to be in progress following detection of the SFD, and it remains in progress until the number of octets specified by the decoded PHR has been received.

A busy channel may be indicated by the PLME-CCA.confirm primitive (6.X.X.X) with a status of BUSY.

A clear channel may be indicated by the PLME-CCA.confirm primitive (6.X.X.X) with a status of IDLE.

The PHY PIB attribute phyCCAMode (see 6.X) may indicate the appropriate operation mode. The CCA parameters are subject to the following criteria:

a) The energy detect threshold may be at most TBD dB above the specified receiver sensitivity (see 6.X.X.X and 6.X.X.X).

b) The CCA detection time may be equal to TBD symbol periods.

6.7.7 Visible/Dimming pattern

The possible Visible Pattern codes that can be used in the Visible Pattern field are shown in Table 6. The code used in the Visible Pattern field is the code specified in the Visible Frame Pattern field of the Control Header field repeated throughout the Visible Pattern field.

We define a set of 11 base visibility patterns based on the 8b10b code to ensure there is no conflict between the visibility pattern and the data transmission at the receiver. We use these base patterns in order to generate high resolution patterns.

Visibility pattern (Percentage visibility)	
11111 11111	(100%)
11110 11111	(90%)
11110 11110	
11101 11100	
11001 11100	
10001 11100	
00001 11100	
00001 11000	
00001 10000	
00001 00000	(10%)
00000 00000	(0%)

Figure 37—Visibility Patterns

In order to generate high resolution visibility patterns, there are certain constraints that need to be used in the design criteria.

- The number of transitions between 0's and 1's must be maximized to provide high frequency switching in order to avoid flicker and to help the CDR circuit at receiver for synchronization purposes, if used.

- Current visibility patterns proposed can have certain properties (visible pattern does not match any existing data pattern out of the 8b10b code). These properties must be preserved with new high resolution patterns.

- Designing a thousand patterns to support low resolutions (as low as 0.1% resolution) is not practical and makes visibility pattern generation and use very complex.

We use existing low resolution patterns to develop high resolution visibility patterns by combining them in multiple ways to generate the required high resolution pattern. For example, if visibility patterns are available at 10% resolution, then a 25% visibility pattern can be attained for example, by alternately sending a 20% visibility pattern followed by a 30% visibility pattern. This method guarantees all frames will retain the same properties as existing visibility frames However, there are multiple ways in which this can be achieved. We provide an algorithm to use at the transmitter to attain the desired visibility. This provides the duty cycle for the visibility required in the shortest amount of time while maximizing the number of transitions and minimizing flicker.

•Dimming or visibility levels: $V_0, V_1, \ldots, V_K$ ($V_0 = 0\%$, $V_K = 100\%$)

• Desired visibility for dimming = dv (percentage)

• Desired precision = p, $p \le 0$, $p \in Z$

Algorithm:

$$\text{sel1pat} = \left\lfloor \frac{dv * K}{100} \right\rfloor$$

$$\text{sel2pat} = \left\lceil \frac{dv * K}{100} \right\rceil$$

$$\text{reppat2} = 10^{-p}\left(dv - \frac{100 * \text{sel1pat}}{K} \right)$$

$$\text{reppat1} = 10^{1-p} - \text{reppat2}$$

repeat V_{sel1pat} reppat1 times

repeat V_{sel2pat} reppat2 times

Figure 38—Generating high resolution visibility patterns

7. MAC sublayer specification

This clause specifies the MAC sublayer of this standard. The MAC sublayer handles all access to the physical radio channel and is responsible for the following tasks:

— Generating network beacons if the device is a coordinator
— Synchronizing to network beacons
— Supporting PAN association and disassociation
— Supporting visibility
— Supporting dimming
— Flicker removal scheme
— Supporting color packets for link establishment and packet error identification
— Supporting device security
— Providing a reliable link between two peer MAC entities
— Supporting mobility

Bi-directional, multicasting and broadcasting capabilities can be provided with a single MAC frame structure. There is a need to support all of these diverse modes into a single, integrated frame structure with low complexity so that devices such as mobile phones can be built to support multiple modes with a single common MAC protocol for area, power and performance benefits. Some aspects could also be made optional for devices that do not wish to support those modes.

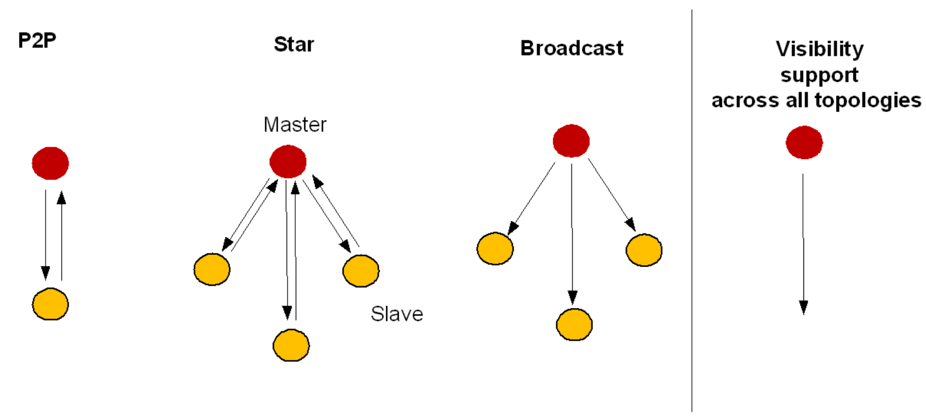


Figure 39—supported MAC topologies

Constants and attributes that are specified and maintained by the MAC sublayer are written in the text of this clause in italics. Constants have a general prefix of “a”, e.g., *aBaseSlotDuration*, and are listed in Table 71 (see 7.5.1). Attributes have a general prefix of “mac”, e.g., *macAckWaitDuration*, and are listed in Table 31 (see 7.5.2), while the security attributes are listed in Table 78 (see 9.8.1).

7.1 MAC sublayer service specification

The MAC sublayer provides an interface between the SSCS and the PHY. The MAC sublayer conceptually includes a management entity called the MLME. This entity provides the service interfaces through which layer management functions may be invoked. The MLME is also responsible for maintaining a database of managed objects pertaining to the MAC sublayer. This database is referred to as the MAC sublayer PIB.

Figure 40 depicts the components and interfaces of the MAC sublayer.

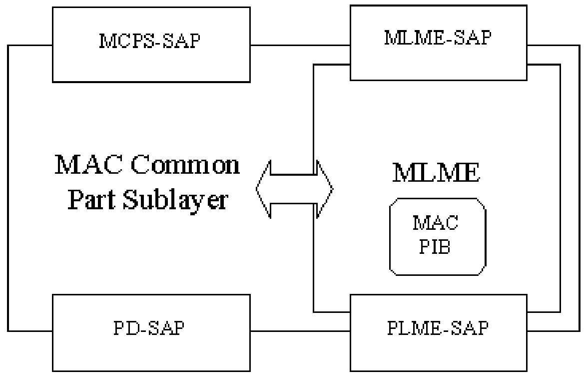


Figure 40—The MAC sublayer reference model

The MAC sublayer provides two services, accessed through two SAPs:

— The MAC data service, accessed through the MAC common part sublayer (MCPS) data SAP (MCPS-SAP), and
— The MAC management service, accessed through the MLME-SAP.

These two services provide the interface between the SSCS and the PHY, via the PD-SAP and PLME-SAP interfaces (see 6.2). In addition to these external interfaces, an implicit interface also exists between the MLME and the MCPS that allows the MLME to use the MAC data service.

7.1.1 MAC data service

The MCPS-SAP supports the transport of SSCS protocol data units (SPDUs) between peer SSCS entities. Table 26 lists the primitives supported by the MCPS-SAP. Primitives marked with a diamond (♦) are optional for an RFD. These primitives are discussed in the subclauses referenced in the table.

Table 26—MCPS-SAP primitives

MCPS-SAP primitive	Request	Confirm	Indication
MCPS-DATA	7.1.1.1	7.1.1.2	7.1.1.3
MCPS-PURGE	7.1.1.4♦	7.1.1.5♦	—

7.1.1.1 MCPS-DATA.request

The MCPS-DATA.request primitive requests the transfer of a data SPDU (i.e., MSDU) from a local SSCS entity to a single peer SSCS entity.

7.1.1.1.1 Semantics of the service primitive

The semantics of the MCPS-DATA.request primitive are as follows:

```
MCPS-DATA.request          (
                           SrcAddrMode,
                           DstAddrMode,
                           DstWPANId,
                           DstAddr,
                           msduLength,
                           msdu,
                           msduHandle,
                           TxOptions,
                           SecurityLevel,
                           KeyIdMode,
                           KeySource,
                           KeyIndex
                           DataRate
                           )
```

Table 27 specifies the parameters for the MCPS-DATA.request primitive.

Table 27—MCPS-DATA.request parameters

Name	Type	Valid range	Description
SrcAddrMode	Integer	0x00–0x03	The source addressing mode for this primitive and subsequent MPDU. This value can take one of the following values: 0x00 = no address (addressing fields omitted, see 7.2.1.1.8). 0x01 = reserved. 0x02 = 16-bit short address. 0x03 = 64-bit extended address.
DstAddrMode	Integer	0x00–0x03	The destination addressing mode for this primitive and subsequent MPDU. This value can take one of the following values: 0x00 = no address (addressing fields omitted, see 7.2.1.1.6). 0x01 = no address field (broadcast only mode with no address fields present). 0x02 = 16-bit short address. 0x03 = 64-bit extended address.
DstWPANId	Integer	0x0000–0xffff	The 16-bit VLC WPAN identifier of the entity to which the MSDU is being transferred.
DstAddr	Device address	As specified by the DstAddrMode parameter	The individual device address of the entity to which the MSDU is being transferred.
msduLength	Integer	≤ *aMaxMACPayloadSize*	The number of octets contained in the MSDU to be transmitted by the MAC sublayer entity.

Table 27—MCPS-DATA.request parameters *(continued)*

Name	Type	Valid range	Description
msdu	Set of octets	—	The set of octets forming the MSDU to be transmitted by the MAC sublayer entity.
msduHandle	Integer	0x00–0xff	The handle associated with the MSDU to be transmitted by the MAC sublayer entity.
TxOptions	Bitmap	3-bit field	The 3 bits (b_0, b_1, b_2) indicate the transmission options for this MSDU. For b_0, 1 = acknowledged transmission, 0 = unacknowledged transmission. For b_1, 1 = GTS transmission, 0 = CAP transmission for a beacon-enabled WPAN. For b_2, 1 = indirect transmission, 0 = direct transmission. For a nonbeacon-enabled WPAN, bit b_1 should always be set to 0.
SecurityLevel	Integer	0x00–0x07	The security level to be used (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key to be used (see Table 86 in 9.8.2.2.2). This parameter is ignored if the SecurityLevel parameter is set to 0x00.
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	The originator of the key to be used (see 9.8.2.4.1). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.
KeyIndex	Integer	0x01–0xff	The index of the key to be used (see 9.8.2.4.2). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.
DataRate	Enumera tion	TBD	The data rate of the PHY frame to be transmitted by the PHY entity.

7.1.1.1.2 Appropriate usage

The MCPS-DATA.request primitive is generated by a local SSCS entity when a data SPDU (i.e., MSDU) is to be transferred to a peer SSCS entity.

7.1.1.1.3 Effect on receipt

On receipt of the MCPS-DATA.request primitive, the MAC sublayer entity begins the transmission of the supplied MSDU.

The MAC sublayer builds an MPDU to transmit from the supplied arguments. The flags in the SrcAddrMode and DstAddrMode parameters correspond to the addressing subfields in the Frame Control field (see 7.2.1.1) and are used to construct both the Frame Control and addressing fields of the MHR. If both the SrcAddrMode and the DstAddrMode parameters are set to 0x00 (i.e., addressing fields omitted), the MAC sublayer will issue the MCPS-DATA.confirm primitive with a status of INVALID_ADDRESS.

If the msduLength parameter is greater than *aMaxMACSafePayloadSize*, the MAC sublayer will set the Frame Version subfield of the Frame Control field to one.

The TxOptions parameter indicates how the MAC sublayer data service transmits the supplied MSDU. If the TxOptions parameter specifies that an acknowledged transmission is required, the Acknowledgment Request subfield of the Frame Control field will be set to one (see 9.7.7.4).

If the TxOptions parameter specifies that a GTS transmission is required, the MAC sublayer will determine whether it has a valid GTS (for GTS usage rules, see 9.7.8.3). If a valid GTS could not be found, the MAC sublayer will issue the MCPS-DATA.confirm primitive with a status of INVALID_GTS. If a valid GTS was found, the MAC sublayer will defer, if necessary, until the GTS. If the TxOptions parameter specifies that a GTS transmission is not required, the MAC sublayer will transmit the MSDU using either slotted random access in the CAP for a beacon-enabled VLC WPAN or unslotted random access for a nonbeacon-enabled VLC WPAN. Specifying a GTS transmission in the TxOptions parameter overrides an indirect transmission request.

If the TxOptions parameter specifies that an indirect transmission is required and this primitive is received by the MAC sublayer of a coordinator, the data frame is sent using indirect transmission, i.e., the data frame is added to the list of pending transactions stored on the coordinator and extracted at the discretion of the device concerned using the method described in 9.7.7.3. Transactions with a broadcast destination address will be transmitted using the mechanism described in 7.2.1.1.3. Transactions with a unicast destination address can then be extracted at the discretion of each device concerned using the method described in 9.7.7.3. If there is no capacity to store the transaction, the MAC sublayer will discard the MSDU and issue the MCPS-DATA.confirm primitive with a status of TRANSACTION_OVERFLOW. If there is capacity to store the transaction, the coordinator will add the information to the list. If the transaction is not handled within *macTransactionPersistenceTime*, the transaction information will be discarded and the MAC sublayer will issue the MCPS-DATA.confirm primitive with a status of TRANSACTION_EXPIRED. The transaction handling procedure is described in 9.7.6. If the TxOptions parameter specifies that an indirect transmission is required and if the device receiving this primitive is not a coordinator, the destination address is not present, or the TxOptions parameter also specifies a GTS transmission, the indirect transmission option will be ignored.

If the TxOptions parameter specifies that an indirect transmission is not required, the MAC sublayer will transmit the MSDU using random access either in the CAP for a beacon-enabled VLC WPAN or immediately for a nonbeacon-enabled VLC WPAN. If the TxOptions parameter specifies that a direct transmission is required and the MAC sublayer does not receive an acknowledgment from the recipient after *macMaxFrameRetries* retransmissions (see 9.7.7.4), it will discard the MSDU and issue the MCPS-DATA.confirm primitive with a status of NO_ACK.

If the SecurityLevel parameter is set to a valid value other than 0x00, indicating that security is required for this frame, the MAC sublayer will set the Security Enabled subfield of the Frame Control field to one. The MAC sublayer will perform outgoing processing on the frame based on the DstAddr, SecurityLevel, KeyIdMode, KeySource, and KeyIndex parameters, as described in 9.7.9.2.1. If any error occurs during outgoing frame processing, the MAC sublayer will discard the frame and issue the MCPS-DATA.confirm primitive with the error status returned by outgoing frame processing.

If the requested transaction is too large to fit in the CAP or GTS, as appropriate, the MAC sublayer shall discard the frame and issue the MCPS-DATA.confirm primitive with a status of FRAME_TOO_LONG.

If the transmission uses random access and the random access algorithm failed due to adverse conditions on the channel, and the TxOptions parameter specifies that a direct transmission is required, the MAC sublayer will discard the MSDU and issue the MCPS-DATA.confirm primitive with a status of CHANNEL_ACCESS_FAILURE.

If the MAC sublayer receives the request while transmission is prohibited it shall delay transmission until transmission is permitted.

If the MPDU was successfully transmitted and, if requested, an acknowledgment was received, the MAC sublayer will issue the MCPS-DATA.confirm primitive with a status of SUCCESS.

If any parameter in the MCPS-DATA.request primitive is not supported or is out of range, the MAC sublayer will issue the MCPS-DATA.confirm primitive with a status of INVALID_PARAMETER.

7.1.1.2 MCPS-DATA.confirm

The MCPS-DATA.confirm primitive reports the results of a request to transfer a data SPDU (MSDU) from a local SSCS entity to a single peer SSCS entity.

7.1.1.2.1 Semantics of the service primitive

The semantics of the MCPS-DATA.confirm primitive are as follows:

```
MCPS-DATA.confirm           (
                            msduHandle,
                            status,
                            Timestamp
                            )
```

Table 28 specifies the parameters for the MCPS-DATA.confirm primitive.

Table 28—MCPS-DATA.confirm parameters

Name	Type	Valid range	Description
msduHandle	Integer	0x00–0xff	The handle associated with the MSDU being confirmed.

Table 28—MCPS-DATA.confirm parameters *(continued)*

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, TRANSACTION_OVERFLOW, TRANSACTION_EXPIRED, CHANNEL_ACCESS_FAILURE, INVALID_ADDRESS, INVALID_GTS, NO_ACK, COUNTER_ERROR, FRAME_TOO_LONG, UNAVAILABLE_KEY, UNSUPPORTED_SECURITY or INVALID_PARAMETER	The status of the last MSDU transmission.
Timestamp	Integer	0x000000–0xffffff	Optional. The time, in symbols, at which the data were transmitted (see 9.7.5.1). The value of this parameter will be considered valid only if the value of the status parameter is SUCCESS; if the status parameter is not equal to SUCCESS, the value of the Timestamp parameter shall not be used for any other purpose. The symbol boundary is described by *macSyncSymbolOffset* (see Table 31 in 7.5.1). This is a 24-bit value, and the precision of this value shall be a minimum of 20 bits, with the lowest 4 bits being the least significant.

7.1.1.2.2 When generated

The MCPS-DATA.confirm primitive is generated by the MAC sublayer entity in response to an MCPS-DATA.request primitive. The MCPS-DATA.confirm primitive returns a status of either SUCCESS, indicating that the request to transmit was successful, or the appropriate error code. The status values are fully described in 7.1.1.1.3 and subclauses referenced by 7.1.1.1.3.

7.1.1.2.3 Appropriate usage

On receipt of the MCPS-DATA.confirm primitive, the SSCS of the initiating device is notified of the result of its request to transmit. If the transmission attempt was successful, the status parameter will be set to SUCCESS. Otherwise, the status parameter will indicate the error.

7.1.1.3 MCPS-DATA.indication

The MCPS-DATA.indication primitive indicates the transfer of a data SPDU (i.e., MSDU) from the MAC sublayer to the local SSCS entity.

7.1.1.3.1 Semantics of the service primitive

The semantics of the MCPS-DATA.indication primitive are as follows:

```
MCPS-DATA.indication          (
                              SrcAddrMode,
                              SrcWPANId,
                              SrcAddr,
                              DstAddrMode,
                              DstWPANId
                              DstAddr,
                              msduLength,
                              msdu,
                              mpduLinkQuality,
                              DSN,
                              Timestamp,
                              SecurityLevel,
                              KeyIdMode,
                              KeySource,
                              KeyIndex
                              DataRate,
                              )
```

Table 29 specifies the parameters for the MCPS-DATA.indication primitive.

Table 29—MCPS-DATA.indication parameters

Name	Type	Valid range	Description
SrcAddrMode	Integer	0x00–0x03	The source addressing mode for this primitive corresponding to the received MPDU. This value can take one of the following values: 0x00 = no address (addressing fields omitted). 0x01 = no address field (broadcast only mode with no address fields present). 0x02 = 16-bit short address. 0x03 = 64-bit extended address.
SrcWPANId	Integer	0x0000–0xffff	The 16-bit WPAN identifier of the entity from which the MSDU was received.
SrcAddr	Device address	As specified by the SrcAddrMode parameter	The individual device address of the entity from which the MSDU was received.

Table 29—MCPS-DATA.indication parameters *(continued)*

Name	Type	Valid range	Description
DstAddrMode	Integer	0x00–0x03	The destination addressing mode for this primitive corresponding to the received MPDU. This value can take one of the following values: 0x00 = no address (addressing fields omitted). 0x01 = no address field (broadcast only mode with no address fields present). 0x02 = 16-bit short device address. 0x03 = 64-bit extended device address.
DstWPANId	Integer	0x0000–0xffff	The 16-bit WPAN identifier of the entity to which the MSDU is being transferred.
DstAddr	Device address	As specified by the DstAddrMode parameter	The individual device address of the entity to which the MSDU is being transferred.
msduLength	Integer	≤ *aMaxMACFrame-Size*	The number of octets contained in the MSDU being indicated by the MAC sublayer entity.
msdu	Set of octets	—	The set of octets forming the MSDU being indicated by the MAC sublayer entity.
mpduLinkQuality	Integer	0x00–0xff	LQI value measured during reception of the MPDU. Lower values represent lower LQI (see 6.13.8).
DSN	Integer	0x00–0xff	The DSN of the received data frame.
Timestamp	Integer	0x000000–0xffffff	Optional. The time, in symbols, at which the data were received (see 9.7.5.1). The symbol boundary is described by *macSyncSymbolOffset* (see Table 31 in 7.5.1). This is a 24-bit value, and the precision of this value shall be a minimum of 20 bits, with the lowest 4 bits being the least significant.
SecurityLevel	Integer	0x00–0x07	The security level purportedly used by the received data frame (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key purportedly used by the originator of the received frame (see Table 86 in 9.8.2.2.2). This parameter is invalid if the SecurityLevel parameter is set to 0x00.
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	The originator of the key purportedly used by the originator of the received frame (see 9.8.2.4.1). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.
KeyIndex	Integer	0x01–0xff	The index of the key purportedly used by the originator of the received frame (see 9.8.2.4.2). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.
DataRate	Enumeration	0, 1, 2, 3, 4	The data rate of the PHY frame received by the PHY entity.

7.1.1.3.2 When generated

The MCPS-DATA.indication primitive is generated by the MAC sublayer and issued to the SSCS on receipt of a data frame at the local MAC sublayer entity that passes the appropriate message filtering operations as described in 9.7.7.2.

7.1.1.3.3 Appropriate usage

On receipt of the MCPS-DATA.indication primitive, the SSCS is notified of the arrival of data at the device. If the primitive is received while the device is in promiscuous mode, the parameters will be set as specified in 9.7.7.5.

7.1.1.4 MCPS-PURGE.request

The MCPS-PURGE.request primitive allows the next higher layer to purge an MSDU from the transaction queue.

This primitive is optional for an RFD.

7.1.1.4.1 Semantics of the service primitive

The semantics of the MCPS-PURGE.request primitive are as follows:

```
MCPS-PURGE.request          (
                            msduHandle
                            )
```

Table 30 specifies the parameters for the MCPS-PURGE.request primitive.

Table 30—MCPS-PURGE.request parameters

Name	Type	Valid range	Description
msduHandle	Integer	0x00–0xff	The handle of the MSDU to be purged from the transaction queue.

7.1.1.4.2 Appropriate usage

The MCPS-PURGE.request primitive is generated by the next higher layer whenever a MSDU is to be purged from the transaction queue.

7.1.1.4.3 Effect on receipt

On receipt of the MCPS-PURGE.request primitive, the MAC sublayer attempts to find in its transaction queue the MSDU indicated by the msduHandle parameter. If an MSDU has left the transaction queue, the handle will not be found, and the MSDU can no longer be purged. If an MSDU matching the given handle is found, the MSDU is discarded from the transaction queue, and the MAC sublayer issues the MCPS-PURGE.confirm primitive with a status of SUCCESS. If an MSDU matching the given handle is not found, the MAC sublayer issues the MCPS-PURGE.confirm primitive with a status of INVALID_HANDLE.

7.1.1.5 MCPS-PURGE.confirm

The MCPS-PURGE.confirm primitive allows the MAC sublayer to notify the next higher layer of the success of its request to purge an MSDU from the transaction queue.

This primitive is optional for an RFD.

7.1.1.5.1 Semantics of the service primitive

The semantics of the MCPS-PURGE.confirm primitive are as follows:

```
MCPS-PURGE.confirm          (
                            msduHandle,
                            status
                            )
```

Table 31 specifies the parameters for the MCPS-PURGE.confirm primitive.

Table 31—MCPS-PURGE.confirm parameters

Name	Type	Valid range	Description
msduHandle	Integer	0x00–0xff	The handle of the MSDU requested to be purge from the transaction queue.
status	Enumeration	SUCCESS or INVALID_HANDLE	The status of the request to be purged an MSDU from the transaction queue.

7.1.1.5.2 When generated

The MCPS-PURGE.confirm primitive is generated by the MAC sublayer entity in response to an MCPS-PURGE.request primitive. The MCPS-PURGE.confirm primitive returns a status of either SUCCESS, indicating that the purge request was successful, or INVALID_HANDLE, indicating an error. The status values are fully described in 7.1.1.4.3.

7.1.1.5.3 Appropriate usage

On receipt of the MCPS-PURGE.confirm primitive, the next higher layer is notified of the result of its request to purge an MSDU from the transaction queue. If the purge request was successful, the status parameter will be set to SUCCESS. Otherwise, the status parameter will indicate the error.

7.1.1.6 Data service message sequence chart

Figure 41 illustrates a sequence of messages necessary for a successful data transfer between two devices. Figure 139 and Figure 140 (see 9.9) also illustrate this, including the steps taken by the PHY.

7.1.2 MAC management service

The MLME-SAP allows the transport of management commands between the next higher layer and the MLME. Table 32 summarizes the primitives supported by the MLME through the MLME-SAP interface. Primitives marked with a diamond (♦) are optional for an RFD. Primitives marked with an asterisk (*) are

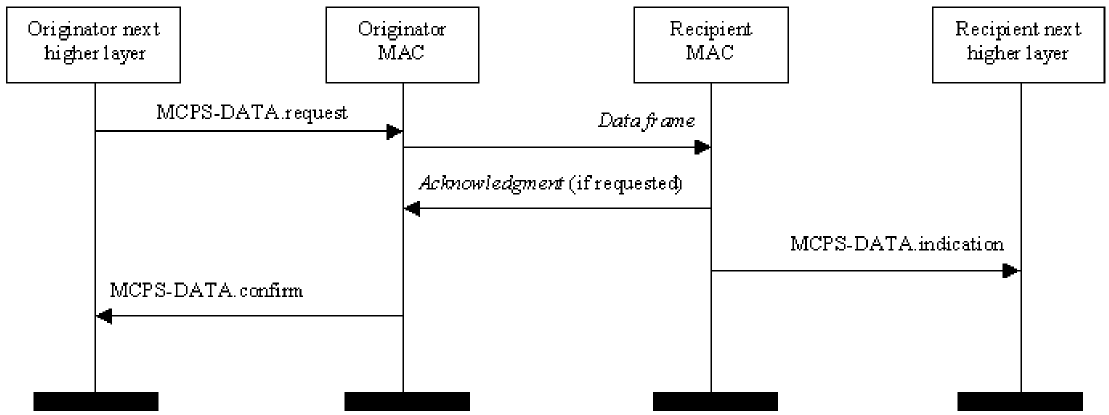


Figure 41—Message sequence chart describing the MAC data service

optional for both device types (i.e., RFD and FFD). The primitives are discussed in the subclauses referenced in the table.

Table 32—Summary of the primitives accessed through the MLME-SAP

Name	Request	Indication	Response	Confirm
MLME-ASSOCIATE	7.1.3.1	7.1.3.2♦	7.1.3.3♦	7.1.3.4
MLME-DISASSOCIATE	7.1.4.1	7.1.4.2		7.1.4.3
MLME-BEACON-NOTIFY		7.1.5.1		
MLME-GET	7.1.6.1			7.1.6.2
MLME-GTS	7.1.7.1*	7.1.7.3*		7.1.7.2*
MLME-ORPHAN		7.1.8.1♦	7.1.8.2♦	
MLME-RESET	7.1.9.1			7.1.9.2
MLME-RX-ENABLE	7.1.10.1*			7.1.10.2*
MLME-SCAN	7.1.11.1			7.1.11.2
MLME-COMM-STATUS		7.1.11.1		
MLME-SET	7.1.12.1			7.1.12.2
MLME-START	7.1.13.1♦			7.1.13.2♦
MLME-SYNC	7.1.14.1*			
MLME-SYNC-LOSS		7.1.14.2		
MLME-POLL	7.1.15.1			7.1.15.2

7.1.3 Association primitives

MLME-SAP association primitives define how a device becomes associated with a VLC WPAN.

All devices shall provide an interface for the request and confirm association primitives. The indication and response association primitives are optional for an RFD.

7.1.3.1 MLME-ASSOCIATE.request

The MLME-ASSOCIATE.request primitive allows a device to request an association with a coordinator.

7.1.3.1.1 Semantics of the service primitive

The semantics of the MLME-ASSOCIATE.request primitive are as follows:

```
MLME-ASSOCIATE.request          (
                                LogicalChannel,
                                CoordAddrMode,
                                CoordWPANId,
                                CoordAddress,
                                CapabilityInformation,
                                SecurityLevel,
                                KeyIdMode,
                                KeySource,
                                KeyIndex
                                )
```

Table 33 specifies the parameters for the MLME-ASSOCIATE.request primitive.

Table 33—MLME-ASSOCIATE.request parameters

Name	Type	Valid range	Description
LogicalChannel	Integer	Selected from the available logical channels supported by the PHY (see 6.1.2).	The logical channel on which to attempt association.
CoordAddrMode	Integer	0x02–0x03	The coordinator addressing mode for this primitive and subsequent MPDU. This value can take one of the following values: 2=16-bit short address. 3=64-bit extended address.
CoordAddress	Device address	As specified by the CoordAddrMode parameter.	The address of the coordinator with which to associate.
CapabilityInformation	Bitmap	See 7.4.1.2	Specifies the operational capabilities of the associating device.
SecurityLevel	Integer	0x00–0x07	The security level to be used (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key to be used (see Table 86 in 9.8.2.2.2). This parameter is ignored if the SecurityLevel parameter is set to 0x00.

Table 33—MLME-ASSOCIATE.request parameters *(continued)*

Name	Type	Valid range	Description
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	The originator of the key to be used (see 9.8.2.4.1). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.
KeyIndex	Integer	0x01–0xff	The index of the key to be used (see 9.8.2.4.2). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.

7.1.3.1.2 Appropriate usage

The MLME-ASSOCIATE.request primitive is generated by the next higher layer of an unassociated device and issued to its MLME to request an association with a VLC WPAN through a coordinator. If the device wishes to associate through a coordinator on a beacon-enabled VLC WPAN, the MLME may optionally track the beacon of that coordinator prior to issuing this primitive.

7.1.3.1.3 Effect on receipt

On receipt of the MLME-ASSOCIATE.request primitive, the MLME of an unassociated device first updates the appropriate PHY and MAC PIB attributes and then generates an association request command (see 7.4.1), as dictated by the association procedure described in 9.7.4.1.

The SecurityLevel parameter specifies the level of security to be applied to the association request command frame. Typically, the association request command should not be implemented using security. However, if the device requesting association shares a key with the coordinator, then security may be specified.

If the SecurityLevel parameter is set to a valid value other than 0x00, indicating that security is required for this frame, the MLME will set the Security Enabled subfield of the Frame Control field to one. The MAC sublayer will perform outgoing processing on the frame based on the CoordAddress, SecurityLevel, KeyIdMode, KeySource, and KeyIndex parameters, as described in 9.7.9.2.1. If any error occurs during outgoing frame processing, the MLME will discard the frame and issue the MLME-ASSOCIATE.confirm primitive with the error status returned by outgoing frame processing.

If the association request command cannot be sent to the coordinator due to the random access algorithm indicating a busy channel, the MLME will issue the MLME-ASSOCIATE.confirm primitive with a status of CHANNEL_ACCESS_FAILURE.

If the MLME successfully transmits an association request command, the MLME will expect an acknowledgment in return. If an acknowledgment is not received, the MLME will issue the MLME-ASSOCIATE.confirm primitive with a status of NO_ACK (see 9.7.7.4).

If the MLME of an unassociated device successfully receives an acknowledgment to its association request command, the MLME will wait for a response to the request (see 9.7.4.1). If the MLME of the device does not receive a response, it will issue the MLME-ASSOCIATE.confirm primitive with a status of NO_DATA.

If the MLME of the device extracts an association response command frame from the coordinator, it will then issue the MLME-ASSOCIATE.confirm primitive with a status equal to the contents of the Association Status field in the association response command (see 7.4.2.3).

On receipt of the association request command, the MLME of the coordinator issues the MLME-ASSOCIATE.indication primitive.

If any parameter in the MLME-ASSOCIATE.request primitive is either not supported or out of range, the MLME will issue the MLME-ASSOCIATE.confirm primitive with a status of INVALID_PARAMETER.

7.1.3.2 MLME-ASSOCIATE.indication

The MLME-ASSOCIATE.indication primitive is used to indicate the reception of an association request command.

7.1.3.2.1 Semantics of the service primitive

The semantics of the MLME-ASSOCIATE.indication primitive are as follows:

```
MLME-ASSOCIATE.indication      (
                               DeviceAddress,
                               CapabilityInformation,
                               SecurityLevel,
                               KeyIdMode,
                               KeySource,
                               KeyIndex
                               )
```

Table 34 specifies the parameters for the MLME-ASSOCIATE.indication primitive.

Table 34—MLME-ASSOCIATE.indication parameters

Name	Type	Valid range	Description
DeviceAddress	Device address	An extended 64-bit IEEE address	The address of the device requesting association.
CapabilityInformation	Bitmap	See 7.4.1.2	The operational capabilities of the device requesting association.
SecurityLevel	Integer	0x00–0x07	The security level purportedly used by the received MAC command frame (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key purportedly used by the originator of the received frame (see Table 86 in 9.8.2.2.2). This parameter is invalid if the SecurityLevel parameter is set to 0x00.
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	The originator of the key purportedly used by the originator of the received frame (see 9.8.2.4.1). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.
KeyIndex	Integer	0x01–0xff	The index of the key purportedly used by the originator of the received frame (see 9.8.2.4.2). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.

7.1.3.2.2 When generated

The MLME-ASSOCIATE.indication primitive is generated by the MLME of the coordinator and issued to its next higher layer to indicate the reception of an association request command (see 7.4.1).

7.1.3.2.3 Appropriate usage

When the next higher layer of a coordinator receives the MLME-ASSOCIATE.indication primitive, the coordinator determines whether to accept or reject the unassociated device using an algorithm outside the scope of this standard. The next higher layer of the coordinator then issues the MLME-ASSOCIATE.response primitive to its MLME.

The association decision and the response should become available at the coordinator within a time of *macResponseWaitTime* (see 9.7.4.1). After this time, the device requesting association attempts to extract the association response command frame from the coordinator, using the method described in 9.7.7.3, in order to determine whether the association was successful.

7.1.3.3 MLME-ASSOCIATE.response

The MLME-ASSOCIATE.response primitive is used to initiate a response to an MLME-ASSOCIATE.indication primitive.

7.1.3.3.1 Semantics of the service primitive

The semantics of the MLME-ASSOCIATE.response primitive are as follows:

```
MLME-ASSOCIATE.response        (
                               DeviceAddress,
                               AssocShortAddress,
                               status,
                               SecurityLevel,
                               KeyIdMode,
                               KeySource,
                               KeyIndex
                               )
```

Table 35 specifies the parameters for the MLME-ASSOCIATE.response primitive.

7.1.3.3.2 Appropriate usage

The MLME-ASSOCIATE.response primitive is generated by the next higher layer of a coordinator and issued to its MLME in order to respond to the MLME-ASSOCIATE.indication primitive.

7.1.3.3.3 Effect on receipt

When the MLME of a coordinator receives the MLME-ASSOCIATE.response primitive, it generates an association response command (see 7.4.2). The command frame is sent to the device requesting association using indirect transmission, i.e., the command frame is added to the list of pending transactions stored on the coordinator and extracted at the discretion of the device concerned using the method described in 9.7.7.3.

If the SecurityLevel parameter is set to a valid value other than 0x00, indicating that security is required for this frame, the MLME will set the Security Enabled subfield of the Frame Control field to one. The MAC sublayer will perform outgoing processing on the frame based the DeviceAddress, SecurityLevel, KeyIdMode, KeySource, and KeyIndex parameters, as described in 9.7.9.2.1. If any error occurs during

Table 35—MLME-ASSOCIATE.response parameters

Name	Type	Valid range	Description
DeviceAddress	Device address	An extended 64 bit IEEE address	The address of the device requesting association.
AssocShortAddress	Integer	0x0000–0xffff	The 16-bit short device address allocated by the coordinator on successful association. This parameter is set to 0xffff if the association was unsuccessful.
status	Enumeration	See 7.4.2.3	The status of the association attempt.
SecurityLevel	Integer	0x00–0x07	The security level to be used (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key to be used (see Table 86 in 9.8.2.2.2). This parameter is ignored if the SecurityLevel parameter is set to 0x00.
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	The originator of the key to be used (see 9.8.2.4.1). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.
KeyIndex	Integer	0x01–0xff	The index of the key to be used (see 9.8.2.4.2). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.

outgoing frame processing, the MLME will discard the frame and issue the MLME-COMM-STATUS.indication primitive with the error status returned by outgoing frame processing.

Upon receipt of the MLME-ASSOCIATE.response primitive, the coordinator attempts to add the information contained in the primitive to its list of pending transactions. If there is no capacity to store the transaction, the MAC sublayer will discard the frame and issue the MLME-COMM-STATUS.indication primitive with a status of TRANSACTION_OVERFLOW. If there is capacity to store the transaction, the coordinator will add the information to the list. If the transaction is not handled within *macTransactionPersistenceTime*, the transaction information will be discarded and the MAC sublayer will issue the MLME-COMM-STATUS.indication primitive with a status of TRANSACTION_EXPIRED. The transaction handling procedure is described in 9.7.6.

If the frame was successfully transmitted and an acknowledgment was received, if requested, the MAC sublayer will issue the MLME-COMM-STATUS.indication primitive with a status of SUCCESS.

If any parameter in the MLME-ASSOCIATE.response primitive is not supported or is out of range, the MAC sublayer will issue the MLME-COMM-STATUS.indication primitive with a status of INVALID_PARAMETER.

7.1.3.4 MLME-ASSOCIATE.confirm

The MLME-ASSOCIATE.confirm primitive is used to inform the next higher layer of the initiating device whether its request to associate was successful or unsuccessful.

7.1.3.4.1 Semantics of the service primitive

The semantics of the MLME-ASSOCIATE.confirm primitive are as follows:

```
MLME-ASSOCIATE.confirm          (
                                AssocShortAddress,
                                status,
                                SecurityLevel,
                                KeyIdMode,
                                KeySource,
                                KeyIndex
                                )
```

Table 36 specifies the parameters for the MLME-ASSOCIATE.confirm primitive.

Table 36—MLME-ASSOCIATE.confirm parameters

Name	Type	Valid range	Description
AssocShortAddress	Integer	0x0000–0xffff	The short device address allocated by the coordinator on successful association. This parameter will be equal to 0xffff if the association attempt was unsuccessful.
status	Enumeration	The value of the Status field of the association response command (see 7.4.2.3), SUCCESS, CHANNEL_ACCESS_FAILURE, NO_ACK, NO_DATA, COUNTER_ERROR, FRAME_TOO_LONG, IMPROPER_KEY_TYPE, IMPROPER_SECURITY_LEVEL, SECURITY_ERROR, UNAVAILABLE_KEY, UNSUPPORTED_LEGACY, UNSUPPORTED_SECURITY INVALID_PARAMETER	The status of the association attempt.
SecurityLevel	Integer	0x00–0x07	If the primitive was generated following failed outgoing processing of an association request command: The security level to be used (see Table 85 in 9.8.2.2.1). If the primitive was generated following receipt of an association response command: The security level purportedly used by the received frame (see Table 85 in 9.8.2.2.1).

Table 36—MLME-ASSOCIATE.confirm parameters *(continued)*

Name	Type	Valid range	Description
KeyIdMode	Integer	0x00–0x03	If the primitive was generated following failed outgoing processing of an association request command: The mode used to identify the key to be used (see Table 86 in 9.8.2.2.2). This parameter is ignored if the SecurityLevel parameter is set to 0x00. If the primitive was generated following receipt of an association response command: The mode used to identify the key purportedly used by the originator of the received frame (see Table 86 in 9.8.2.2.2). This parameter is invalid if the SecurityLevel parameter is set to 0x00.
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	If the primitive was generated following failed outgoing processing of an association request command: The originator of the key to be used (see 9.8.2.4.1). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00. If the primitive was generated following receipt of an association response command: The originator of the key purportedly used by the originator of the received frame (see 9.8.2.4.1). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.
KeyIndex	Integer	0x01–0xff	If the primitive was generated following failed outgoing processing of an association request command: The index of the key to be used (see 9.8.2.4.2). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00. If the primitive was generated following receipt of an association response command: The index of the key purportedly used by the originator of the received frame (see 9.8.2.4.2). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.

7.1.3.4.2 When generated

The MLME-ASSOCIATE.confirm primitive is generated by the initiating MLME and issued to its next higher layer in response to an MLME-ASSOCIATE.request primitive. If the request was successful, the status parameter will indicate a successful association, as contained in the Status field of the association response command. Otherwise, the status parameter indicates either an error code from the received association response command or the appropriate error code from Table 36. The status values are fully described in 7.1.3.1.3 and subclauses referenced by 7.1.3.1.3.

7.1.3.4.3 Appropriate usage

On receipt of the MLME-ASSOCIATE.confirm primitive, the next higher layer of the initiating device is notified of the result of its request to associate with a coordinator. If the association attempt was successful, the status parameter will indicate a successful association, as contained in the Status field of the association response command, and the device will be provided with a 16-bit short address (see Table 77 in 9.7.4.1). If the association attempt was unsuccessful, the address will be equal to 0xffff, and the status parameter will indicate the error.

7.1.3.5 Association message sequence charts

Figure 42 illustrates a sequence of messages that may be used by a device that is not tracking the beacon of the coordinator (see 9.7.7.3) to successfully associate with a VLC WPAN. Figure 135 and Figure 136 (see 9.9) illustrate this same scenario, including steps taken by the PHY, for a device associating with a coordinator and for a coordinator allowing association by a device, respectively.

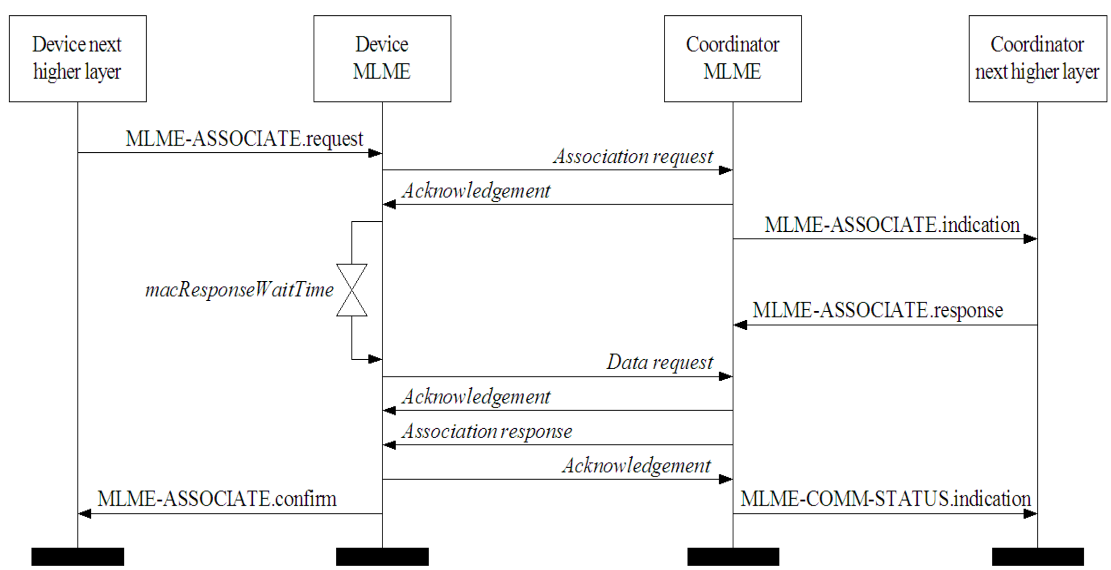


Figure 42—Message sequence chart for association

7.1.4 Disassociation primitives

The MLME-SAP disassociation primitives define how a device can disassociate from a VLC WPAN.

All devices shall provide an interface for these disassociation primitives.

7.1.4.1 MLME-DISASSOCIATE.request

The MLME-DISASSOCIATE.request primitive is used by an associated device to notify the coordinator of its intent to leave the VLC WPAN. It is also used by the coordinator to instruct an associated device to leave the VLC WPAN.

7.1.4.1.1 Semantics of the service primitive

The semantics of the MLME-DISASSOCIATE.request primitive are as follows:

```
MLME-DISASSOCIATE.request      (
                               DeviceAddrMode,
                               DeviceWPANId,
                               DeviceAddress,
                               DisassociateReason,
                               TxIndirect,
                               SecurityLevel,
                               KeyIdMode,
                               KeySource,
                               KeyIndex
                               )
```

Table 37 specifies the parameters for the MLME-DISASSOCIATE.request primitive.

7.1.4.1.2 Appropriate usage

The MLME-DISASSOCIATE.request primitive is generated by the next higher layer of an associated device and issued to its MLME to request disassociation from the VLC WPAN. It is also generated by the next higher layer of the coordinator and issued to its MLME to instruct an associated device to leave the VLC WPAN.

7.1.4.1.3 Effect on receipt

On receipt of the MLME-DISASSOCIATE.request primitive, the MLME compares the DeviceWPANId parameter with *macWPANId*. If the DeviceWPANId parameter is not equal to *macWPANId*, the MLME issues the MLME-DISASSOCIATE.confirm primitive with a status of INVALID_PARAMETER. If the DeviceWPANId parameter is equal to *macWPANId*, the MLME evaluates the primitive address fields.

If the DeviceAddrMode parameter is equal to 0x02 and the DeviceAddress parameter is equal to *macCoordShortAddress* or if the DeviceAddrMode parameter is equal to 0x03 and the DeviceAddress parameter is equal to *macCoordExtendedAddress*, the TxIndirect parameter is ignored, and the MLME sends a disassociation notification command (see 7.4.3) to its coordinator in the CAP for a beacon-enabled VLC WPAN or immediately for a nonbeacon-enabled VLC WPAN.

If the DeviceAddrMode parameter is equal to 0x02 and the DeviceAddress parameter is not equal to *macCoordShortAddress* or if the DeviceAddrMode parameter is equal to 0x03 and the DeviceAddress parameter is not equal to *macCoordExtendedAddress*, and if this primitive was received by the MLME of a coordinator with the TxIndirect parameter set to TRUE, the disassociation notification command will be sent using indirect transmission, i.e., the command frame is added to the list of pending transactions stored on the coordinator and extracted at the discretion of the device concerned using the method described in 9.7.7.3.

If the DeviceAddrMode parameter is equal to 0x02 and the DeviceAddress parameter is not equal to *macCoordShortAddress* or if the DeviceAddrMode parameter is equal to 0x03 and the DeviceAddress

Table 37—MLME-DISASSOCIATE.request parameters

Name	Type	Valid range	Description
DeviceAddrMode	Integer	0x02–0x03	The addressing mode of the device to which to send the disassociation notification command.
DeviceWPANId	Integer	0x0000–0xffff	The WPAN identifier of the device to which to send the disassociation notification command.
DeviceAddress	Device address	As specified by the DeviceAddrMode parameter.	The address of the device to which to send the disassociation notification command.
DisassociateReason	Integer	0x00–0xff	The reason for the disassociation (see 7.4.3.2).
TxIndirect	Boolean	TRUE or FALSE	TRUE if the disassociation notification command is to be sent indirectly.
SecurityLevel	Integer	0x00–0x07	The security level to be used (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key to be used (see Table 86 in 9.8.2.2.2). This parameter is ignored if the SecurityLevel parameter is set to 0x00.
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	The originator of the key to be used (see 9.8.2.4.1). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.
KeyIndex	Integer	0x01–0xff	The index of the key to be used (see 9.8.2.4.2). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.

parameter is not equal to *macCoordExtendedAddress*, and if this primitive was received by the MLME of a coordinator with the TxIndirect parameter set to FALSE, the MLME sends a disassociation notification command to the device in the CAP for a beacon-enabled VLC WPAN or immediately for a nonbeacon-enabled VLC WPAN.

Otherwise, the MLME issues the MLME-DISASSOCIATE.confirm primitive with a status of INVALID_PARAMETER and does not generate a disassociation notification command.

If the disassociation notification command is to be sent using indirect transmission and there is no capacity to store the transaction, the MLME will discard the frame and issue the MLME-DISASSOCIATE.confirm primitive with a status of TRANSACTION_OVERFLOW. If there is capacity to store the transaction, the coordinator will add the information to the list. If the transaction is not handled within *macTransaction-PersistenceTime*, the transaction information will be discarded, and the MLME will issue the MLME-DISASSOCIATE.confirm with a status of TRANSACTION_EXPIRED. The transaction handling procedure is described in 9.7.6.

If the disassociation notification command cannot be sent due to a random access algorithm failure and this primitive was received either by the MLME of a coordinator with the TxIndirect parameter set to FALSE or by the MLME of a device, the MLME will issue the MLME-DISASSOCIATE.confirm primitive with a status of CHANNEL_ACCESS_FAILURE.

If the SecurityLevel parameter is set to a valid value other than 0x00, indicating that security is required for this frame, the MLME will set the Security Enabled subfield of the Frame Control field to one. The MAC sublayer will perform outgoing processing on the frame based on the DeviceAddress, SecurityLevel, KeyIdMode, KeySource, and KeyIndex parameters, as described in 9.7.9.2.1. If any error occurs during outgoing frame processing, the MLME will discard the frame and issue the MLME-DISASSOCIATE.confirm primitive with the error status returned by outgoing frame processing.

If the MLME successfully transmits a disassociation notification command, the MLME will expect an acknowledgment in return. If an acknowledgment is not received and this primitive was received either by the MLME of a coordinator with the TxIndirect parameter set to FALSE or by the MLME of a device, the MLME will issue the MLME-DISASSOCIATE.confirm primitive with a status of NO_ACK (see 9.7.7.4).

If the MLME successfully transmits a disassociation notification command and receives an acknowledgment in return, the MLME will issue the MLME-DISASSOCIATE.confirm primitive with a status of SUCCESS.

On receipt of the disassociation notification command, the MLME of the recipient issues the MLME-DISASSOCIATE.indication primitive.

If any parameter in the MLME-DISASSOCIATE.request primitive is not supported or is out of range, the MLME will issue the MLME-DISASSOCIATE.confirm primitive with a status of INVALID_PARAMETER.

7.1.4.2 MLME-DISASSOCIATE.indication

The MLME-DISASSOCIATE.indication primitive is used to indicate the reception of a disassociation notification command.

7.1.4.2.1 Semantics of the service primitive

The semantics of the MLME-DISASSOCIATE.indication primitive are as follows:

```
MLME-DISASSOCIATE.indication    (
                                DeviceAddress,
                                DisassociateReason,
                                SecurityLevel,
                                KeyIdMode,
                                KeySource,
                                KeyIndex
                                )
```

Table 38 specifies the parameters for the MLME-DISASSOCIATE.indication primitive.

7.1.4.2.2 When generated

The MLME-DISASSOCIATE.indication primitive is generated by the MLME and issued to its next higher layer on receipt of a disassociation notification command.

7.1.4.2.3 Appropriate usage

The next higher layer is notified of the reason for the disassociation.

Table 38—MLME-DISASSOCIATE.indication parameters

Name	Type	Valid range	Description
DeviceAddress	Device address	An extended 64-bit IEEE address	The address of the device requesting disassociation.
DisassociateReason	Integer	0x00–0xff	The reason for the disassociation (see 7.4.3.2).
SecurityLevel	Integer	0x00–0x07	The security level purportedly used by the received MAC command frame (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key purportedly used by the originator of the received frame (see Table 86 in 9.8.2.2.2). This parameter is invalid if the SecurityLevel parameter is set to 0x00.
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	The originator of the key purportedly used by the originator of the received frame (see 9.8.2.4.1). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.
KeyIndex	Integer	0x01–0xff	The index of the key purportedly used by the originator of the received frame (see 9.8.2.4.2). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.

7.1.4.3 MLME-DISASSOCIATE.confirm

The MLME-DISASSOCIATE.confirm primitive reports the results of an MLME-DISASSOCIATE.request primitive.

7.1.4.3.1 Semantics of the service primitive

The semantics of the MLME-DISASSOCIATE.confirm primitive are as follows:

```
MLME-DISASSOCIATE.confirm     (
                              status,
                              DeviceAddrMode,
                              DevicePANId,
                              DeviceAddress
                              )
```

Table 39 specifies the parameters for the MLME-DISASSOCIATE.confirm primitive.

7.1.4.3.2 When generated

The MLME-DISASSOCIATE.confirm primitive is generated by the initiating MLME and issued to its next higher layer in response to an MLME-DISASSOCIATE.request primitive. This primitive returns a status of either SUCCESS, indicating that the disassociation request was successful, or the appropriate error code. The status values are fully described in 7.1.4.1.3 and subclauses referenced by 7.1.4.1.3.

Table 39—MLME-DISASSOCIATE.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, TRANSACTION_OVERFLOW, TRANSACTION_EXPIRED, NO_ACK, CHANNEL_ACCESS_FAILURE, COUNTER_ERROR, FRAME_TOO_LONG, UNAVAILABLE_KEY, UNSUPPORTED_SECURITY or INVALID_PARAMETER	The status of the disassociation attempt.
DeviceAddrMode	Integer	0x02–0x03	The addressing mode of the device that has either requested disassociation or been instructed to disassociate by its coordinator.
DeviceWPANId	Integer	0x0000–0xffff	The WPAN identifier of the device that has either requested disassociation or been instructed to disassociate by its coordinator.
DeviceAddress	Device address	As specified by the DeviceAddrMode parameter.	The address of the device that has either requested disassociation or been instructed to disassociate by its coordinator.

7.1.4.3.3 Appropriate usage

On receipt of the MLME-DISASSOCIATE.confirm primitive, the next higher layer of the initiating device is notified of the result of the disassociation attempt. If the disassociation attempt was successful, the status parameter will be set to SUCCESS. Otherwise, the status parameter indicates the error.

7.1.4.4 Disassociation message sequence charts

The request to disassociate may originate either from a device or from the coordinator through which the device has associated. Figure 43 illustrates the sequence of messages necessary for a device to successfully disassociate itself from the VLC WPAN.

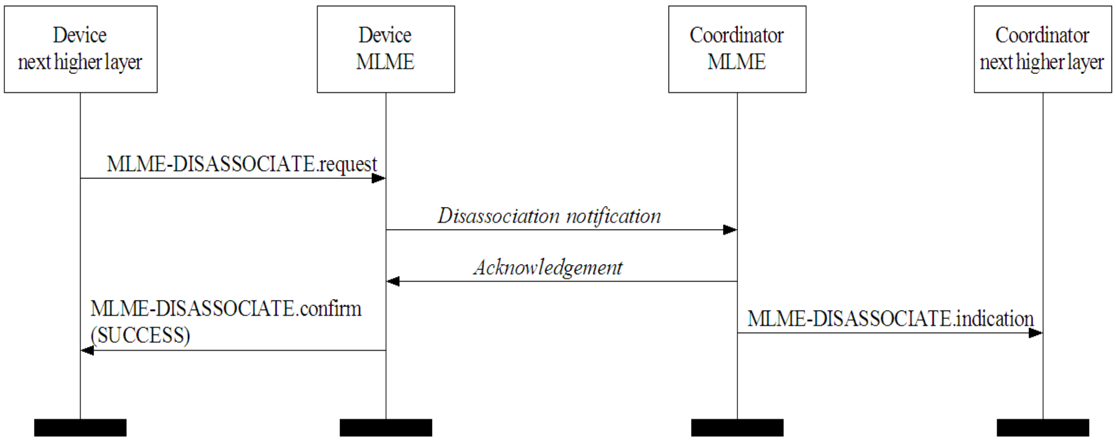


Figure 43—Message sequence chart for disassociation initiated by a device

Figure 44 illustrates the sequence necessary for a coordinator in a beacon-enabled VLC WPAN to successfully disassociate a device from its VLC WPAN using indirect transmission.

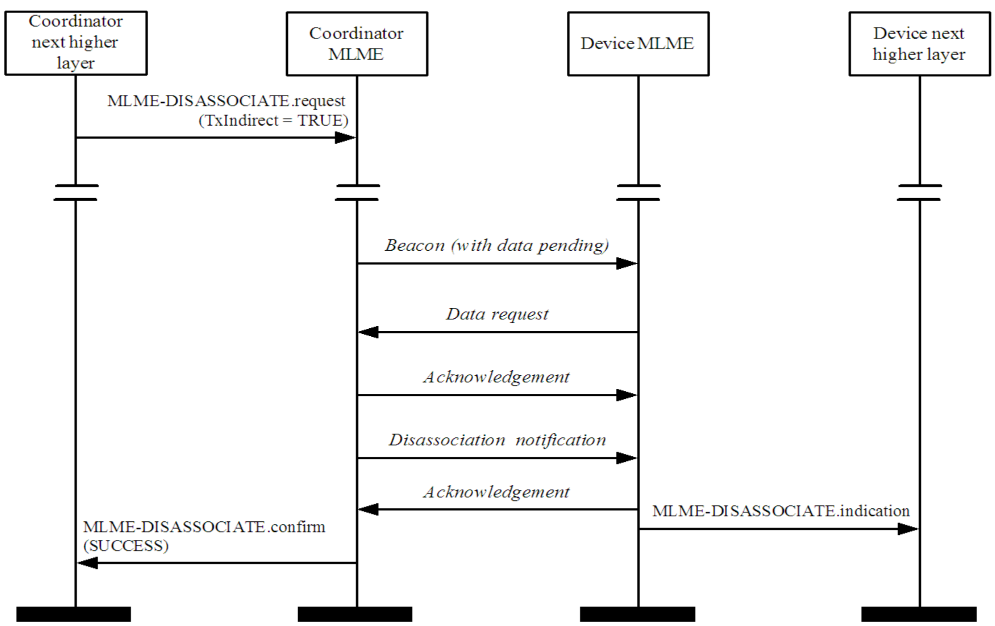


Figure 44—Message sequence chart for disassociation initiated by a coordinator, using indirect transmission, in a beacon-enabled VLC WPAN

7.1.5 Beacon notification primitive

The MLME-SAP beacon notification primitive defines how a device may be notified when a beacon is received during normal operating conditions.

All devices shall provide an interface for the beacon notification primitive.

7.1.5.1 MLME-BEACON-NOTIFY.indication

The MLME-BEACON-NOTIFY.indication primitive is used to send parameters contained within a beacon frame received by the MAC sublayer to the next higher layer. The primitive also sends a measure of the LQI and the time the beacon frame was received.

7.1.5.1.1 Semantics of the service primitive

The semantics of the MLME-BEACON-NOTIFY.indication primitive are as follows:

```
MLME-BEACON-NOTIFY.indication   (
                                BSN,
                                WPANDescriptor,
                                PendAddrSpec,
                                AddrList,
                                sduLength,
                                sdu
                                )
```

Table 40 specifies the parameters for the MLME-BEACON-NOTIFY.indication primitive.

Table 40—MLME-BEACON-NOTIFY.indication parameters

Name	Type	Valid range	Description
BSN	Integer	0x00–0xff	The beacon sequence number.
WPANDescriptor	WPANDescriptor value	See Table 41	The WPANDescriptor for the received beacon.
PendAddrSpec	Bitmap	See 7.2.2.1.6	The beacon pending address specification.
AddrList	List of device addresses	—	The list of addresses of the devices for which the beacon source has data.
sduLength	Integer	0 – *aMaxBeaconPayloadLength*	The number of octets contained in the beacon payload of the beacon frame received by the MAC sublayer.
sdu	Set of octets	—	The set of octets comprising the beacon payload to be transferred from the MAC sublayer entity to the next higher layer.

Table 41 describes the elements of the WPANDescriptor type.

Table 41—Elements of WPAN Descriptor

Name	Type	Valid range	Description
CoordAddrMode	Integer	0x02–0x03	The coordinator addressing mode corresponding to the received beacon frame. This value can take one of the following values: 2 = 16-bit short address. 3 = 64-bit extended address.
CoordWPANId	Integer	0x0000–0xffff	The WPAN identifier of the coordinator as specified in the received beacon frame.
CoordAddress	Device address	As specified by the CoordAddrMode parameter	The address of the coordinator as specified in the received beacon frame.
LogicalChannel	Integer	Selected from the available logical channels supported by the PHY (see 6.1.2)	The current logical channel occupied by the network.
SuperframeSpec	Bitmap	See 7.2.2.1.2	The superframe specification as specified in the received beacon frame.
GTSPermit	Boolean	TRUE or FALSE	TRUE if the beacon is from the coordinator that is accepting GTS requests.
LinkQuality	Integer	0x00–0xff	The LQI at which the network beacon was received. Lower values represent lower LQI (see 6.13.8).
TimeStamp	Integer	0x000000–0xffffff	The time at which the beacon frame was received, in symbols. This value is equal to the timestamp taken when the beacon frame was received, as described in 9.7.5.1. This is a 24-bit value, and the precision of this value shall be a minimum of 20 bits, with the lowest 4 bits being the least significant.
SecurityFailure	Enumer-ation	SUCCESS, COUNTER_ERROR, IMPROPER_KEY_TYPE, IMPROPER_SECURITY_LEVEL, SECURITY_ERROR, UNAVAILABLE_KEY, UNSUPPORTED_LEGACY, UNSUPPORTED_SECURITY	SUCCESS if there was no error in the security processing of the frame. One of the other status codes indicating an error in the security processing otherwise (see 9.7.9.2.3).
SecurityLevel	Integer	0x00–0x07	The security level purportedly used by the received beacon frame (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key purportedly used by the originator of the received frame (see Table 86 in 9.8.2.2.2). This parameter is invalid if the SecurityLevel parameter is set to 0x00.

Table 41—Elements of WPAN Descriptor *(continued)*

Name	Type	Valid range	Description
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	The originator of the key purportedly used by the originator of the received frame (see 9.8.2.4.1). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.
KeyIndex	Integer	0x01–0xff	The index of the key purportedly used by the originator of the received frame (see 9.8.2.4.2). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.

7.1.5.1.2 When generated

The MLME-BEACON-NOTIFY.indication primitive is generated by the MLME and issued to its next higher layer upon receipt of a beacon frame either when *macAutoRequest* is set to FALSE or when the beacon frame contains one or more octets of payload.

7.1.5.1.3 Appropriate usage

On receipt of the MLME-BEACON-NOTIFY.indication primitive, the next higher layer is notified of the arrival of a beacon frame at the MAC sublayer.

7.1.6 Primitives for reading PIB attributes

The MLME-SAP get primitives define how to read values from the PIB.

All devices shall provide an interface for these get primitives.

7.1.6.1 MLME-GET.request

The MLME-GET.request primitive requests information about a given PIB attribute.

7.1.6.1.1 Semantics of the service primitive

The semantics of the MLME-GET.request primitive are as follows:

```
MLME-GET.request          (
                          PIBAttribute,
                          PIBAttributeIndex
                          )
```

Table 42 specifies the parameters for the MLME-GET.request primitive.

7.1.6.1.2 Appropriate usage

The MLME-GET.request primitive is generated by the next higher layer and issued to its MLME to obtain information from the PIB.

Table 42—MLME-GET.request parameters

Name	Type	Valid range	Description
PIBAttribute	Integer	See Table 31 and Table 78	The identifier of the PIB attribute to read.
PIBAttributeIndex	Integer	Attribute specific; see Table 78	The index within the table of the specified PIB attribute to read. This parameter is valid only for MAC PIB attributes that are tables; it is ignored when accessing PHY PIB attributes.

7.1.6.1.3 Effect on receipt

On receipt of the MLME-GET.request primitive, the MLME checks to see if the PIB attribute is a MAC PIB attribute or PHY PIB attribute. If the requested attribute is a MAC attribute, the MLME attempts to retrieve the requested MAC PIB attribute from its database. If the identifier of the PIB attribute is not found in the database, the MLME will issue the MLME-GET.confirm primitive with a status of UNSUPPORTED_ATTRIBUTE. If the PIBAttributeIndex parameter specifies an index for a table that is out of range, the MLME will issue the MLME-GET.confirm primitive with a status of INVALID_INDEX. If the requested MAC PIB attribute is successfully retrieved, the MLME will issue the MLME-GET.confirm primitive with a status of SUCCESS.

If the requested attribute is a PHY PIB attribute, the request is passed to the PHY by issuing the PLME-GET.request primitive. Once the MLME receives the PLME-GET.confirm primitive, it will translate the received status value because the status values used by the PHY are not the same as those used by the MLME (e.g., the status values for SUCCESS are 0x00 and 0x07 in the MAC and PHY enumeration tables, respectively). Following the translation, the MLME will issue the MLME-GET.confirm primitive to the next higher layer with the status parameter resulting from the translation and the PIBAttribute and PIBAttributeValue parameters equal to those returned by the PLME primitive.

7.1.6.2 MLME-GET.confirm

The MLME-GET.confirm primitive reports the results of an information request from the PIB.

7.1.6.2.1 Semantics of the service primitive

The semantics of the MLME-GET.confirm primitive are as follows:

```
MLME-GET.confirm          (
                          status,
                          PIBAttribute,
                          PIBAttributeIndex,
                          PIBAttributeValue
                          )
```

Table 43 specifies the parameters for the MLME-GET.confirm primitive.

7.1.6.2.2 When generated

The MLME-GET.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-GET.request primitive. This primitive returns a status of either SUCCESS, indicating that the request to read a PIB attribute was successful, or an error code of UNSUPPORTED_ATTRIBUTE.

Table 43—MLME-GET.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, UNSUPPORTED_ATTRIBUTE or INVALID_INDEX	The result of the request for PIB attribute information.
PIBAttribute	Integer	See Table 31 and Table 78	The identifier of the PIB attribute that was read.
PIBAttributeIndex	Integer	Attribute specific; see Table 78	The index within the table or array of the specified PIB attribute to read. This parameter is valid only for MAC PIB attributes that are tables or arrays; it is ignored when accessing PHY PIB attributes.
PIBAttributeValue	Various	Attribute specific; see Table 31 and Table 78	The value of the indicated PIB attribute that was read. This parameter has zero length when the status parameter is set to UNSUPPORTED_ATTRIBUTE.

When an error code of UNSUPPORTED_ATTRIBUTE is returned, the PIBAttribute value parameter will be set to length zero. The status values are fully described in 7.1.6.1.3.

7.1.6.2.3 Appropriate usage

On receipt of the MLME-GET.confirm primitive, the next higher layer is notified of the results of its request to read a PIB attribute. If the request to read a PIB attribute was successful, the status parameter will be set to SUCCESS. Otherwise, the status parameter indicates the error.

7.1.7 GTS management primitives

The MLME-SAP GTS management primitives define how GTSs are requested and maintained. A device wishing to use these primitives and GTSs in general will already be tracking the beacons of its coordinator.

These GTS management primitives are optional.

7.1.7.1 MLME-GTS.request

The MLME-GTS.request primitive allows a device to send a request to the coordinator to allocate a new GTS or to deallocate an existing GTS. This primitive is also used by the coordinator to initiate a GTS deallocation.

7.1.7.1.1 Semantics of the service primitive

The semantics of the MLME-GTS.request primitive are as follows:

```
MLME-GTS.request            (
                            GTSCharacteristics,
                            SecurityLevel,
                            KeyIdMode,
                            KeySource,
                            KeyIndex
                            )
```

Table 44 specifies the parameters for the MLME-GTS.request primitive.

Table 44—MLME-GTS.request parameters

Name	Type	Valid range	Description
GTSCharacteristics	GTS characteristics	See 7.4.13.2	The characteristics of the GTS request, including whether the request is for the allocation of a new GTS or the deallocation of an existing GTS.
SecurityLevel	Integer	0x00–0x07	The security level to be used (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key to be used (see Table 86 in 9.8.2.2.2). This parameter is ignored if the SecurityLevel parameter is set to 0x00.
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	The originator of the key to be used (see 9.8.2.4.1). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.
KeyIndex	Integer	0x01–0xff	The index of the key to be used (see 9.8.2.4.2). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.

7.1.7.1.2 Appropriate usage

The MLME-GTS.request primitive is generated by the next higher layer of a device and issued to its MLME to request the allocation of a new GTS or to request the deallocation of an existing GTS. It is also generated by the next higher layer of the coordinator and issued to its MLME to request the deallocation of an existing GTS.

7.1.7.1.3 Effect on receipt

On receipt of the MLME-GTS.request primitive by a device, the MLME of a device attempts to generate a GTS request command (see 7.4.13) with the information contained in this primitive and, if successful, sends it to the coordinator.

If *macShortAddress* is equal to 0xfffe or 0xffff, the device is not permitted to request a GTS. In this case, the MLME issues the MLME-GTS.confirm primitive containing a status of NO_SHORT_ADDRESS.

If the SecurityLevel parameter is set to a valid value other than 0x00, indicating that security is required for this frame, the MLME will set the Security Enabled subfield of the Frame Control field to one. The MAC sublayer will perform outgoing processing on the frame based on *macCoordExtendedAddress* and the SecurityLevel, KeyIdMode, KeySource, and KeyIndex parameters, as described in 9.7.9.2.1. If any error occurs during outgoing frame processing, the MLME will discard the frame and issue the MLME-GTS.confirm primitive with the error status returned by outgoing frame processing.

If the GTS request command cannot be sent due to a random access algorithm failure, the MLME will issue the MLME-GTS.confirm primitive with a status of CHANNEL_ACCESS_FAILURE.

If the MLME successfully transmits a GTS request command, the MLME will expect an acknowledgment in return. If an acknowledgment is not received, the MLME will issue the MLME-GTS.confirm primitive with a status of NO_ACK (see 9.7.7.4).

If a GTS is being allocated (see 9.7.8.2) and the request has been acknowledged, the device will wait for a confirmation via a GTS descriptor specified in a beacon frame from its coordinator. If the MLME of the coordinator can allocate the requested GTS, it will issue the MLME-GTS.indication primitive with the characteristics of the allocated GTS and generate a GTS descriptor with the characteristics of the allocated GTS and the 16-bit short address of the requesting device. If the MLME of the coordinator cannot allocate the requested GTS, it will generate a GTS descriptor with a start slot of zero and the short address of the requesting device.

If the device receives a beacon frame from its coordinator with a GTS descriptor containing a 16-bit short address that matches *macShortAddress*, the device will process the descriptor. If no descriptor for that device is received, the MLME will issue the MLME-GTS.confirm primitive with a status of NO_DATA.

If a descriptor is received that matches the characteristics requested (indicating that the coordinator has approved the GTS allocation request), the MLME of the device will issue the MLME-GTS.confirm primitive with a status of SUCCESS and a GTSCharacteristics parameter with a characteristics type equal to one, indicating a GTS allocation.

If the descriptor is received with a start slot of zero (indicating that the coordinator has denied the GTS allocation request), the device requesting the GTS issues the MLME-GTS.confirm primitive with a status of DENIED, indicating that the GTSCharacteristics parameter is to be ignored.

If a GTS is being deallocated (see 9.7.8.4) at the request of a device and the request has been acknowledged by the coordinator, the device will issue the MLME-GTS.confirm primitive with a status of SUCCESS and a GTSCharacteristics parameter with a characteristics type equal to zero, indicating a GTS deallocation. On receipt of a GTS request command with a request type indicating a GTS deallocation, the coordinator will acknowledge the frame and deallocates the GTS. The MLME of the coordinator will then issue the MLME-GTS.indication primitive with the appropriate GTS characteristics. If the coordinator does not receive the deallocation request, countermeasures can be applied by the coordinator to ensure consistency is maintained (see 9.7.8.6).

If the MLME of the coordinator receives an MLME-GTS.request primitive indicating deallocation, the coordinator will deallocate the GTS and issue the MLME-GTS.confirm primitive with a status of SUCCESS and a GTSCharacteristics parameter with a characteristics type equal to zero.

If the device receives a beacon frame from its coordinator with a GTS descriptor containing a short address that matches *macShortAddress* and a start slot equal to zero, the device immediately stops using the GTS. The MLME of the device then notifies the next higher layer of the deallocation by issuing the MLME-GTS.indication primitive with a GTSCharacteristics parameter containing the characteristics of the deallocated GTS.

If any parameter in the MLME-GTS.request primitive is not supported or is out of range, the MLME will issue the MLME-GTS.confirm primitive with a status of INVALID_PARAMETER.

7.1.7.2 MLME-GTS.confirm

The MLME-GTS.confirm primitive reports the results of a request to allocate a new GTS or deallocate an existing GTS.

7.1.7.2.1 Semantics of the service primitive

The semantics of the MLME-GTS.confirm primitive are as follows:

```
MLME-GTS.confirm          (
                          GTSCharacteristics,
                          status
                          )
```

Table 45 specifies the parameters for the MLME-GTS.confirm primitive.

Table 45—MLME-GTS.confirm parameters

Name	Type	Valid range	Description
GTSCharacteristics	GTS characteristics	See 7.4.13.2	The characteristics of the GTS.
status	Enumeration	SUCCESS, DENIED, NO_SHORT_ADDRESS, CHANNEL_ACCESS_FAILURE, NO_ACK, NO_DATA, COUNTER_ERROR, FRAME_TOO_LONG, UNAVAILABLE_KEY, UNSUPPORTED_SECURITY or INVALID_PARAMETER.	The status of the GTS request.

7.1.7.2.2 When generated

The MLME-GTS.confirm primitive is generated by the MLME and issued to its next higher layer in response to a previously issued MLME-GTS.request primitive.

If the request to allocate or deallocate a GTS was successful, this primitive will return a status of SUCCESS and the Characteristics Type field of the GTSCharacteristics parameter will have the value of one or zero, respectively. Otherwise, the status parameter will indicate the appropriate error code. The reasons for these status values are fully described in 7.1.7.1.3 and subclauses referenced by 7.1.7.1.3.

7.1.7.2.3 Appropriate usage

On receipt of the MLME-GTS.confirm primitive the next higher layer is notified of the result of its request to allocate or deallocate a GTS. If the request was successful, the status parameter will indicate a successful GTS operation. Otherwise, the status parameter will indicate the error.

7.1.7.3 MLME-GTS.indication

The MLME-GTS.indication primitive indicates that a GTS has been allocated or that a previously allocated GTS has been deallocated.

7.1.7.3.1 Semantics of the service primitive

The semantics of the MLME-GTS.indication primitive are as follows:

```
MLME-GTS.indication          (
                             DeviceAddress,
                             GTSCharacteristics,
                             SecurityLevel,
                             KeyIdMode,
                             KeySource,
                             KeyIndex
                             )
```

Table 46 specifies the parameters for the MLME-GTS.indication primitive.

Table 46—MLME-GTS.indication parameters

Name	Type	Valid range	Description
DeviceAddress	Device address	0x0000–0xfffd	The 16-bit short address of the device that has been allocated or deallocated a GTS.
GTSCharacteristics	GTS characteristics	See 7.4.13.2	The characteristics of the GTS.
SecurityLevel	Integer	0x00–0x07	If the primitive was generated when a GTS deallocation is initiated by the coordinator itself, the security level to be used is set to 0x00. If the primitive was generated whenever a GTS is allocated or deallocated following the reception of a GTS request command: The security level purportedly used by the received MAC command frame (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	If the primitive was generated when a GTS deallocation is initiated by the coordinator itself, this parameter is ignored. If the primitive was generated whenever a GTS is allocated or deallocated following the reception of a GTS request command: The mode used to identify the key purportedly used by the originator of the received frame (see Table 86 in 9.8.2.2.2). This parameter is invalid if the SecurityLevel parameter is set to 0x00.

Table 46—MLME-GTS.indication parameters *(continued)*

Name	Type	Valid range	Description
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	If the primitive was generated when a GTS deallocation is initiated by the coordinator itself, this parameter is ignored. If the primitive was generated whenever a GTS is allocated or deallocated following the reception of a GTS request command: The originator of the key purportedly used by the originator of the received frame (see 9.8.2.4.1). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.
KeyIndex	Integer	0x01–0xff	If the primitive was generated when a GTS deallocation is initiated by the coordinator itself, this parameter is ignored. If the primitive was generated whenever a GTS is allocated or deallocated following the reception of a GTS request command: The index of the key purportedly used by the originator of the received frame (see 9.8.2.4.2). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.

7.1.7.3.2 When generated

The MLME-GTS.indication primitive is generated by the MLME of the coordinator to its next higher layer whenever a GTS is allocated or deallocated following the reception of a GTS request command (see 7.4.13) by the MLME. The MLME of the coordinator also generates this primitive when a GTS deallocation is initiated by the coordinator itself. The Characteristics Type field in the GTSCharacteristics parameter will be equal to one if a GTS has been allocated or zero if a GTS has been deallocated.

This primitive is generated by the MLME of a device and issued to its next higher layer when the coordinator has deallocated one of its GTSs. In this case, the Characteristics Type field of the GTSCharacteristics parameter is equal to zero.

7.1.7.3.3 Appropriate usage

On receipt of the MLME-GTS.indication primitive the next higher layer is notified of the allocation or de-allocation of a GTS.

7.1.7.4 GTS management message sequence charts

Figure 45 and Figure 46 illustrate the sequence of messages necessary for successful GTS management. The first depicts the message flow for the case in which the device initiates the GTS allocation. The second depicts the message flow for the two cases for which a GTS deallocation occurs, first, by a device (a) and, second, by the coordinator (b).

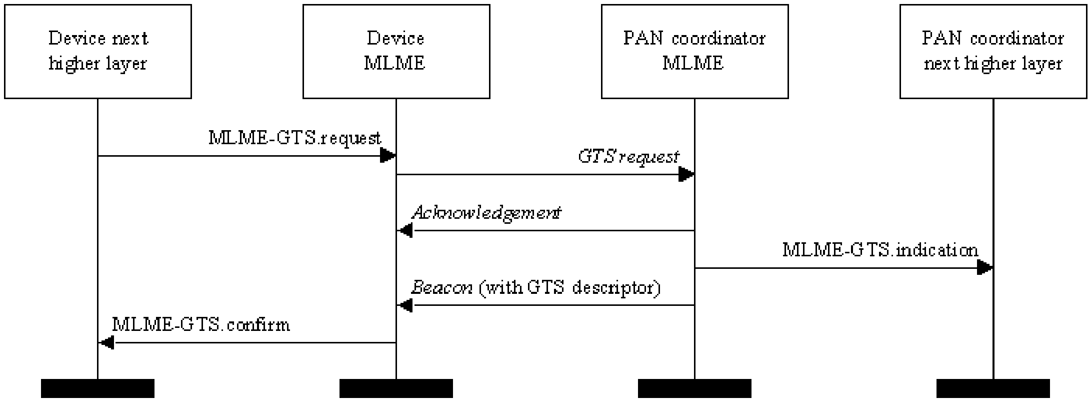


Figure 45—Message sequence chart for GTS allocation initiated by a device

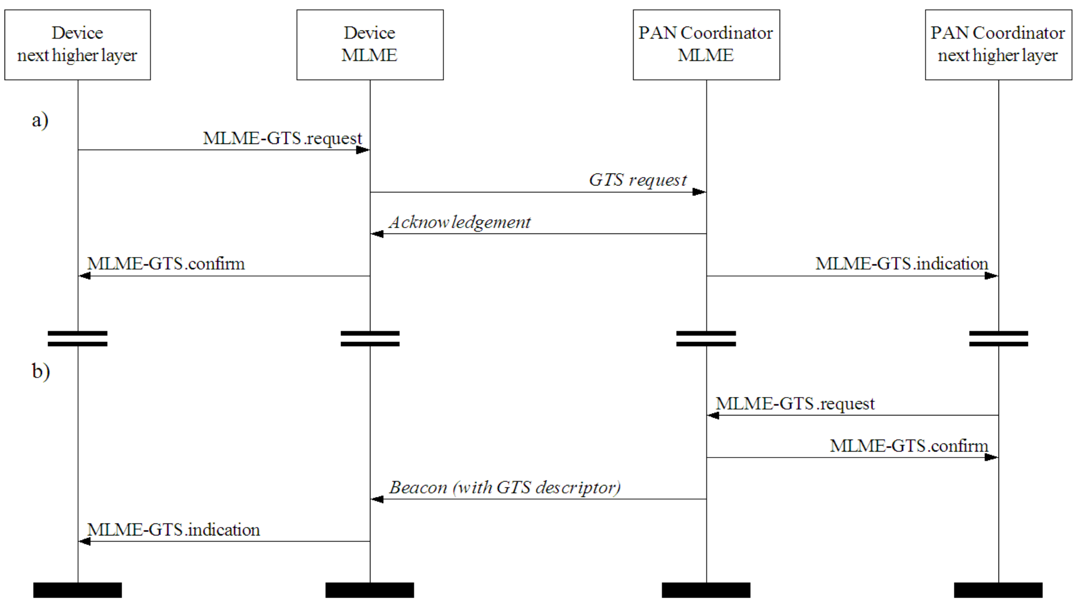


Figure 46—Message sequence chart for GTS deallocation initiated by a device (a) and the PAN coordinator (b)

7.1.8 Primitives for orphan notification

MLME-SAP orphan notification primitives define how a coordinator can issue a notification of an orphaned device.

These orphan notification primitives are optional for an RFD.

7.1.8.1 MLME-ORPHAN.indication

The MLME-ORPHAN.indication primitive allows the MLME of a coordinator to notify the next higher layer of the presence of an orphaned device.

7.1.8.1.1 Semantics of the service primitive

The semantics of the MLME-ORPHAN.indication primitive are as follows:

```
MLME-ORPHAN.indication        (
                              OrphanAddress,
                              SecurityLevel,
                              KeyIdMode,
                              KeySource,
                              KeyIndex
                              )
```

Table 47 specifies the parameters for the MLME-ORPHAN.indication primitive.

Table 47—MLME-ORPHAN.indication parameters

Name	Type	Valid range	Description
OrphanAddress	Device address	Extended 64-bit IEEE address	The address of the orphaned device.
SecurityLevel	Integer	0x00–0x07	The security level purportedly used by the received MAC command frame (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key purportedly used by the originator of the received frame (see Table 86 in 9.8.2.2.2). This parameter is invalid if the SecurityLevel parameter is set to 0x00.
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	The originator of the key purportedly used by the originator of the received frame (see 9.8.2.4.1). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.
KeyIndex	Integer	0x01–0xff	The index of the key purportedly used by the originator of the received frame (see 9.8.2.4.2). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.

7.1.8.1.2 When generated

The MLME-ORPHAN.indication primitive is generated by the MLME of a coordinator and issued to its next higher layer on receipt of an orphan notification command (see 7.4.6).

7.1.8.1.3 Appropriate usage

The effect on receipt of the MLME-ORPHAN.indication primitive is that the next higher layer is notified of the orphaned device. The next higher layer then determines whether the device was previously associated and issues the MLME-ORPHAN.response primitive to the MLME with its decision (see 7.5.2.1.4).

If the device was previously associated with the coordinator, it will send the MLME-ORPHAN.response primitive with the AssociatedMember parameter set to TRUE and the ShortAddress parameter set to the corresponding 16-bit short address allocated to the orphaned device. If the device was not previously associated with the coordinator, it will send the MLME-ORPHAN.response primitive with the AssociatedMember parameter set to FALSE.

7.1.8.2 MLME-ORPHAN.response

The MLME-ORPHAN.response primitive allows the next higher layer of a coordinator to respond to the MLME-ORPHAN.indication primitive.

7.1.8.2.1 Semantics of the service primitive

The semantics of the MLME-ORPHAN.response primitive are as follows:

```
MLME-ORPHAN.response        (
                            OrphanAddress,
                            ShortAddress,
                            AssociatedMember,
                            SecurityLevel,
                            KeyIdMode,
                            KeySource,
                            KeyIndex
                            )
```

Table 48 specifies the parameters for the MLME-ORPHAN.response primitive.

Table 48—MLME-ORPHAN.response parameters

Name	Type	Valid range	Description
OrphanAddress	Device address	Extended 64-bit IEEE address	The address of the orphaned device.
ShortAddress	Integer	0x0000–0xffff	The 16-bit short address allocated to the orphaned device if it is associated with this coordinator. The special short address 0xfffe indicates that no short address was allocated, and the device will use its 64-bit extended address in all communications. If the device was not associated with this coordinator, this field will contain the value 0xffff and be ignored on receipt.
AssociatedMember	Boolean	TRUE or FALSE	TRUE if the orphaned device is associated with this coordinator or FALSE otherwise.
SecurityLevel	Integer	0x00–0x07	The security level to be used (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key to be used (see Table 86 in 9.8.2.2.2). This parameter is ignored if the SecurityLevel parameter is set to 0x00.

Table 48—MLME-ORPHAN.response parameters *(continued)*

Name	Type	Valid range	Description
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	The originator of the key to be used (see 9.8.2.4.1). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.
KeyIndex	Integer	0x01–0xff	The index of the key to be used (see 9.8.2.4.2). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.

7.1.8.2.2 Appropriate usage

The MLME-ORPHAN.response primitive is generated by the next higher layer and issued to its MLME when it reaches a decision about whether the orphaned device indicated in the MLME-ORPHAN.indication primitive is associated.

7.1.8.2.3 Effect on receipt

If the AssociatedMember parameter is set to TRUE, the orphaned device is associated with the coordinator. In this case, the MLME generates and sends the coordinator realignment command (see 7.4.8) to the orphaned device containing the value of the ShortAddress field. This command is sent in the CAP if the coordinator is on a beacon-enabled VLC WPAN or immediately otherwise. If the AssociatedMember parameter is set to FALSE, the orphaned device is not associated with the coordinator and this primitive will be ignored. If the orphaned device does not receive the coordinator realignment command following its orphan notification within *macResponseWaitTime* symbols, it will assume it is not associated to any coordinator in range.

If the SecurityLevel parameter is set to a valid value other than 0x00, indicating that security is required for this frame, the MLME will set the Security Enabled subfield of the Frame Control field to one. The MAC sublayer will perform outgoing processing on the frame based on the OrphanAddress, SecurityLevel, KeyIdMode, KeySource, and KeyIndex parameters, as described in 9.7.9.2.1. If any error occurs during outgoing frame processing, the MLME will discard the frame and issue the MLME-COMM-STATUS.indication primitive with the error status returned by outgoing frame processing.

If the random access algorithm failed due to adverse conditions on the channel, the MAC sublayer will discard the frame and issue the MLME-COMM-STATUS.indication primitive with a status of CHANNEL_ACCESS_FAILURE.

The MAC sublayer enables its receiver immediately following the transmission of the frame and waits for an acknowledgment from the recipient (see 9.7.7.4). If the MAC sublayer does not receive an acknowledgment from the recipient, it will discard the frame and issue the MLME-COMM-STATUS.indication primitive with a status of NO_ACK.

If the frame was successfully transmitted and an acknowledgment was received, if requested, the MAC sublayer will issue the MLME-COMM-STATUS.indication primitive with a status of SUCCESS.

If any parameter in the MLME-ORPHAN.response primitive is not supported or is out of range, the MAC sublayer will issue the MLME-COMM-STATUS.indication primitive with a status of INVALID_PARAMETER.

7.1.8.3 Orphan notification message sequence chart

Figure 47 illustrates the sequence of messages necessary for a coordinator to issue a notification of an orphaned device.

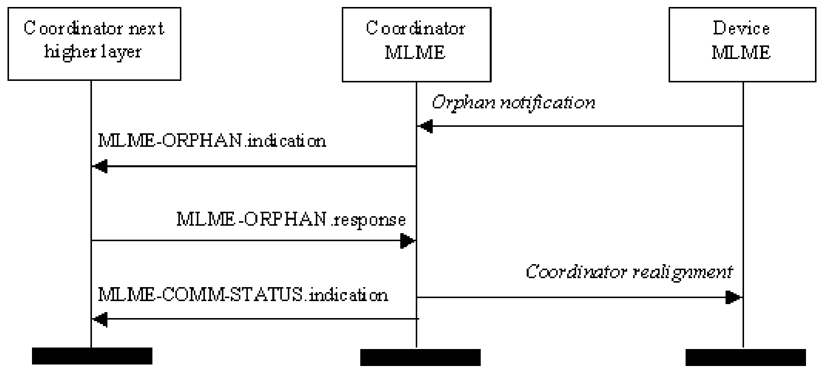


Figure 47—Message sequence chart for orphan notification

7.1.9 Primitives for resetting the MAC sublayer

MLME-SAP reset primitives specify how to reset the MAC sublayer to its default values.

All devices shall provide an interface for these reset primitives.

7.1.9.1 MLME-RESET.request

The MLME-RESET.request primitive allows the next higher layer to request that the MLME performs a reset operation.

7.1.9.1.1 Semantics of the service primitive

The semantics of the MLME-RESET.request primitive are as follows:

```
MLME-RESET.request          (
                            SetDefaultPIB
                            )
```

Table 49 specifies the parameter for the MLME-RESET.request primitive.

Table 49—MLME-RESET.request parameter

Name	Type	Valid range	Description
SetDefaultPIB	Boolean	TRUE or FALSE	If TRUE, the MAC sublayer is reset, and all MAC PIB attributes are set to their default values. If FALSE, the MAC sublayer is reset, but all MAC PIB attributes retain their values prior to the generation of the MLME-RESET.request primitive.

7.1.9.1.2 Appropriate usage

The MLME-RESET.request primitive is generated by the next higher layer and issued to the MLME to request a reset of the MAC sublayer to its initial conditions. The MLME-RESET.request primitive is issued prior to the use of the MLME-START.request or the MLME-ASSOCIATE.request primitives.

7.1.9.1.3 Effect on receipt

On receipt of the MLME-RESET.request primitive, the MLME issues the PLME-SET-TRX-STATE.request primitive with a state of FORCE_TRX_OFF. On receipt of the PLME-SET-TRX-STATE.confirm primitive, the MAC sublayer is then set to its initial conditions, clearing all internal variables to their default values. If the SetDefaultPIB parameter is set to TRUE, the MAC PIB attributes are set to their default values.

The MLME-RESET.confirm primitive with a status of SUCCESS is issued on completion.

7.1.9.2 MLME-RESET.confirm

The MLME-RESET.confirm primitive reports the results of the reset operation.

7.1.9.2.1 Semantics of the service primitive

The semantics of the MLME-RESET.confirm primitive are as follows:

```
MLME-RESET.confirm          (
                            status
                            )
```

Table 50 specifies the parameter for the MLME-RESET.confirm primitive.

Table 50—MLME-RESET.confirm parameter

Name	Type	Valid range	Description
status	Enumeration	SUCCESS	The result of the reset operation.

7.1.9.2.2 When generated

The MLME-RESET.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-RESET.request primitive and following the receipt of the PLME-SET-TRX-STATE.confirm primitive.

7.1.9.2.3 Appropriate usage

On receipt of the MLME-RESET.confirm primitive, the next higher layer is notified of its request to reset the MAC sublayer. This primitive returns a status of SUCCESS indicating that the request to reset the MAC sublayer was successful.

7.1.10 Primitives for channel scanning

TBD

7.1.11 Communication status primitive

The MLME-SAP communication status primitive defines how the MLME communicates to the next higher layer about transmission status, when the transmission was instigated by a response primitive, and about security errors on incoming packets.

All devices shall provide an interface for this communication status primitive.

7.1.11.1 MLME-COMM-STATUS.indication

The MLME-COMM-STATUS.indication primitive allows the MLME to indicate a communications status.

7.1.11.1.1 Semantics of the service primitive

The semantics of the MLME-COMM-STATUS.indication primitive are as follows:

```
MLME-COMM-STATUS.indication    (
                               WPANId,
                               SrcAddrMode,
                               SrcAddr,
                               DstAddrMode,
                               DstAddr,
                               status,
                               SecurityLevel,
                               KeyIdMode,
                               KeySource,
                               KeyIndex
                               )
```

Table 51 specifies the parameters for the MLME-COMM-STATUS.indication primitive.

Table 51—MLME-COMM-STATUS.indication parameters

Name	Type	Valid range	Description
WPANId	Integer	0x0000–0xffff	The 16-bit WPAN identifier of the device from which the frame was received or to which the frame was being sent.
SrcAddrMode	Integer	0x00–0x03	The source addressing mode for this primitive. This value can take one of the following values: 0 = no address (addressing fields omitted). 0x01 = no address field (broadcast only mode with no address fields present). 0x02 = 16-bit short address. 0x03 = 64-bit extended address.
SrcAddr	Device address	As specified by the SrcAddrMode parameter	The individual device address of the entity from which the frame causing the error originated.

Table 51—MLME-COMM-STATUS.indication parameters *(continued)*

Name	Type	Valid range	Description
DstAddrMode	Integer	0x00–0x03	The destination addressing mode for this primitive. This value can take one of the following values: 0x00 = no address (addressing fields omitted). 0x01 = reserved. 0x02 = 16-bit short address. 0x03 = 64-bit extended address.
DstAddr	Device address	As specified by the DstAddrMode parameter	The individual device address of the device for which the frame was intended.
status	Enumeration	SUCCESS, TRANSACTION_OVERFLOW, TRANSACTION_EXPIRED, CHANNEL_ACCESS_FAILURE, NO_ACK, COUNTER_ERROR, FRAME_TOO_LONG, IMPROPER_KEY_TYPE, IMPROPER_SECURITY_LEVEL, SECURITY_ERROR, UNAVAILABLE_KEY, UNSUPPORTED_LEGACY, UNSUPPORTED_SECURITY or INVALID_PARAMETER	The communications status.
SecurityLevel	Integer	0x00–0x07	If the primitive was generated following a transmission instigated through a response primitive: The security level to be used (see Table 85 in 9.8.2.2.1). If the primitive was generated on receipt of a frame that generates an error in its security processing: The security level purportedly used by the received frame (see Table 85 in 9.8.2.2.1).

Table 51—MLME-COMM-STATUS.indication parameters *(continued)*

Name	Type	Valid range	Description
KeyIdMode	Integer	0x00–0x03	If the primitive was generated following a transmission instigated through a response primitive: The mode used to identify the key to be used (see Table 86 in 9.8.2.2.2). This parameter is ignored if the SecurityLevel parameter is set to 0x00. If the primitive was generated on receipt of a frame that generates an error in its security processing: The mode used to identify the key purportedly used by the originator of the received frame (see Table 86 in 9.8.2.2.2). This parameter is invalid if the SecurityLevel parameter is set to 0x00.
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	If the primitive was generated following a transmission instigated through a response primitive: The originator of the key to be used (see 9.8.2.4.1). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00. If the primitive was generated on receipt of a frame that generates an error in its security processing: The originator of the key purportedly used by the originator of the received frame (see 9.8.2.4.1). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.
KeyIndex	Integer	0x01–0xff	If the primitive was generated following a transmission instigated through a response primitive: The index of the key to be used (see 9.8.2.4.2). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00. If the primitive was generated on receipt of a frame that generates an error in its security processing: The index of the key purportedly used by the originator of the received frame (see 9.8.2.4.2). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.

7.1.11.1.2 When generated

The MLME-COMM-STATUS.indication primitive is generated by the MLME and issued to its next higher layer either following a transmission instigated through a response primitive or on receipt of a frame that generates an error in its security processing (see 9.7.9.2.3).

The MLME-COMM-STATUS.indication primitive is generated by the MAC sublayer entity following either the MLME-ASSOCIATE.response primitive or the MLME-ORPHAN.response primitive. This primitive returns a status of either SUCCESS, indicating that the request to transmit was successful, an error code of TRANSACTION_OVERFLOW, TRANSACTION_EXPIRED, CHANNEL_ACCESS_FAILURE, NO_ACK or INVALID_PARAMETER (these status values are fully described in 7.1.3.3.3 and 7.1.8.2.3), or an error code resulting from failed security processing (these status values are fully described in 9.7.9.2.1 and 9.7.9.2.3).

7.1.11.1.3 Appropriate usage

On receipt of the MLME-COMM-STATUS.indication primitive, the next higher layer is notified of the communication status of a transmission or notified of an error that has occurred during the secure processing of incoming frame.

7.1.12 Primitives for writing PIB attributes

MLME-SAP set primitives define how PIB attributes may be written.

All devices shall provide an interface for these set primitives.

7.1.12.1 MLME-SET.request

The MLME-SET.request primitive attempts to write the given value to the indicated PIB attribute.

7.1.12.1.1 Semantics of the primitive

The semantics of the MLME-SET.request primitive are as follows:

```
MLME-SET.request          (
                          PIBAttribute,
                          PIBAttributeIndex,
                          PIBAttributeValue
                          )
```

Table 52 specifies the parameters for the MLME-SET.request primitive.

7.1.12.1.2 Appropriate usage

The MLME-SET.request primitive is generated by the next higher layer and issued to its MLME to write the indicated PIB attribute.

7.1.12.1.3 Effect on receipt

On receipt of the MLME-SET.request primitive, the MLME checks to see if the PIB attribute is a MAC PIB attribute or PHY PIB attribute. If the requested attribute is a MAC attribute, the MLME attempts to write the given value to the indicated MAC PIB attribute in its database. If the PIBAttribute parameter specifies an attribute that is a read-only attribute (see Table 31 and Table 78), the MLME will issue the MLME-SET.confirm primitive with a status of READ_ONLY. If the PIBAttribute parameter specifies an attribute

Table 52—MLME-SET.request parameters

Name	Type	Valid range	Description
PIBAttribute	Integer	See Table 31 and Table 78	The identifier of the PIB attribute to write.
PIBAttributeIndex	Integer	Attribute specific; see Table 78	The index within the table of the specified PIB attribute to write. This parameter is valid only for MAC PIB attributes that are tables; it is ignored when accessing PHY PIB attributes.
PIBAttributeValue	Various	Attribute specific; see Table 31 and Table 78	The value to write to the indicated PIB attribute.

that is not found in the database, the MLME will issue the MLME-SET.confirm primitive with a status of UNSUPPORTED_ATTRIBUTE. If the PIBAttributeIndex parameter specifies an index for a table that is out of range, the MLME will issue the MLME-SET.confirm primitive with a status of INVALID_INDEX. If the PIBAttributeValue parameter specifies a value that is out of the valid range for the given attribute, the MLME will issue the MLME-SET.confirm primitive with a status of INVALID_PARAMETER. If the requested MAC PIB attribute is successfully written, the MLME will issue the MLME-SET.confirm primitive with a status of SUCCESS.

If the PIBAttribute parameter indicates that *macBeaconPayloadLength* is to be set and the length of the resulting beacon frame exceeds *aMaxPHYPacketSize* (e.g., due to the additional overhead required for security processing), the MAC sublayer shall not update *macBeaconPayloadLength* and will issue the MLME-GET.confirm primitive with a status of INVALID_PARAMETER.

If the requested attribute is a PHY PIB attribute, the request is passed to the PHY by issuing the PLME-SET.request primitive. Once the MLME receives the PLME-SET.confirm primitive, it will translate the received status value because the status values used by the PHY are not the same as those used by the MLME (e.g., the status values for SUCCESS are 0x00 and 0x07 in the MAC and PHY enumeration tables, respectively). Following the translation, the MLME will issue the MLME-SET.confirm primitive to the next higher layer with the status parameter resulting from the translation and the PIBAttribute parameter equal to that returned by the PLME primitive.

7.1.12.2 MLME-SET.confirm

The MLME-SET.confirm primitive reports the results of an attempt to write a value to a PIB attribute.

7.1.12.2.1 Semantics of the service primitive

The semantics of the MLME-SET.confirm primitive are as follows:

```
MLME-SET.confirm          (
                          status,
                          PIBAttribute,
                          PIBAttributeIndex
                          )
```

Table 53 specifies the parameters for the MLME-SET.confirm primitive.

Table 53—MLME-SET.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, READ_ONLY, UNSUPPORTED_ATTRIBUTE, INVALID_INDEX or INVALID_PARAMETER	The result of the request to write the PIB attribute.
PIBAttribute	Integer	See Table 31 and Table 78	The identifier of the PIB attribute that was written.
PIBAttributeIndex	Integer	Attribute specific; see Table 78	The index within the table of the specified PIB attribute to write. This parameter is valid only for MAC PIB attributes that are tables; it is ignored when accessing PHY PIB attributes.

7.1.12.2.2 When generated

The MLME-SET.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-SET.request primitive. The MLME-SET.confirm primitive returns a status of either SUCCESS, indicating that the requested value was written to the indicated PIB attribute, or the appropriate error code. The status values are fully described in 7.1.12.1.3.

7.1.12.2.3 Appropriate usage

On receipt of the MLME-SET.confirm primitive, the next higher layer is notified of the result of its request to set the value of a PIB attribute. If the requested value was written to the indicated PIB attribute, the status parameter will be set to SUCCESS. Otherwise, the status parameter indicates the error.

7.1.13 Primitives for updating the superframe configuration

MLME-SAP start primitives define how an FFD can request to start using a new superframe configuration in order to initiate a VLC WPAN, begin transmitting beacons on an already existing VLC WPAN, thus facilitating device discovery, or to stop transmitting beacons.

These start primitives are optional for an RFD.

7.1.13.1 MLME-START.request

The MLME-START.request primitive allows the VLC coordinator to initiate a new VLC WPAN or to begin using a new superframe configuration. This primitive may also be used by a device already associated with an existing VLC WPAN to begin using a new superframe configuration.

7.1.13.1.1 Semantics of the service primitive

The semantics of the MLME-START.request primitive are as follows:

```
MLME-START.request          (
                            WPANId,
                            LogicalChannel,
                            StartTime,
                            BeaconOrder,
                            SuperframeOrder,
                            WPANCoordinator,
                            CoordRealignment,
                            CoordRealignSecurityLevel,
                            CoordRealignKeyIdMode,
                            CoordRealignKeySource,
                            CoordRealignKeyIndex,
                            BeaconSecurityLevel,
                            BeaconKeyIdMode,
                            BeaconKeySource,
                            BeaconKeyIndex
                            )
```

Table 54 specifies the parameters for the MLME-START.request primitive.

Table 54—MLME-START.request parameters

Name	Type	Valid range	Description
WPANId	Integer	0x0000–0xffff	The WPAN identifier to be used by the device.
LogicalChannel	Integer	Selected from the available logical channels specified by the ChannelPage parameter	The logical channel on which to start using the new superframe configuration.
ChannelPage	Integer	Selected from the available channel pages supported by the PHY (see 6.1.2)	The channel page on which to begin using the new superframe configuration.

Table 54—MLME-START.request parameters *(continued)*

Name	Type	Valid range	Description
StartTime	Integer	0x000000–0xffffff	The time at which to begin transmitting beacons. If this parameter is equal to 0x000000, beacon transmissions will begin immediately. Otherwise, the specified time is relative to the received beacon of the coordinator with which the device synchronizes. This parameter is ignored if either the BeaconOrder parameter has a value of 15 or the WPANCoordinator parameter is TRUE. The time is specified in symbols and is rounded to a backoff slot boundary. This is a 24-bit value, and the precision of this value shall be a minimum of 20 bits, with the lowest 4 bits being the least significant.
BeaconOrder	Integer	0–15	How often the beacon is to be transmitted. A value of 15 indicates that the coordinator will not transmit periodic beacons. See 7.7.1.1 for an explanation of the relationship between the beacon order and the beacon interval.
SuperframeOrder	Integer	0–*BO* or 15	The length of the active portion of the superframe, including the beacon frame. If the BeaconOrder parameter (*BO*) has a value of 15, this parameter is ignored. See 7.7.1.1 for an explanation of the relationship between the superframe order and the superframe duration.
WPANCoordinator	Boolean	TRUE or FALSE	If this value is TRUE, the device will become the coordinator of a new WPAN. If this value is FALSE, the device will begin using a new superframe configuration on the WPAN with which it is associated.
CoordRealignment	Boolean	TRUE or FALSE	TRUE if a coordinator realignment command is to be transmitted prior to changing the superframe configuration or FALSE otherwise.
CoordRealignSecurity-Level	Integer	0x00–0x07	The security level to be used for coordinator realignment command frames (see Table 85 in 9.8.2.2.1).

Table 54—MLME-START.request parameters *(continued)*

Name	Type	Valid range	Description
CoordRealignKeyId-Mode	Integer	0x00–0x03	The mode used to identify the key to be used (see Table 86 in 9.8.2.2.2). This parameter is ignored if the CoordRealignSecurityLevel parameter is set to 0x00.
CoordRealignKey-Source	Set of 0, 4, or 8 octets	As specified by the CoordRealignKeyIdMode parameter	The originator of the key to be used (see 9.8.2.4.1). This parameter is ignored if the CoordRealignKeyId-Mode parameter is ignored or set to 0x00.
CoordRealignKeyIndex	Integer	0x01–0xff	The index of the key to be used (see 9.8.2.4.2). This parameter is ignored if the CoordRealignKeyIdMode parameter is ignored or set to 0x00.
BeaconSecurityLevel	Integer	0x00–0x07	The security level to be used for beacon frames (see Table 85 in 9.8.2.2.1).
BeaconKeyIdMode	Integer	0x00–0x03	The mode used to identify the key to be used (see Table 86 in 9.8.2.2.2). This parameter is ignored if the BeaconSecurityLevel parameter is set to 0x00.
BeaconKeySource	Set of 0, 4, or 8 octets	As specified by the BeaconKeyIdMode parameter	The originator of the key to be used (see 9.8.2.4.1). This parameter is ignored if the BeaconKeyIdMode parameter is ignored or set to 0x00.
BeaconKeyIndex	Integer	0x01–0xff	The index of the key to be used (see 9.8.2.4.2). This parameter is ignored if the BeaconKeyIdMode parameter is ignored or set to 0x00.

7.1.13.1.2 Appropriate usage

The MLME-START.request primitive is generated by the next higher layer and issued to its MLME to request that a device start using a new superframe configuration.

7.1.13.1.3 Effect on receipt

If the MLME-START.request primitive is received when *macShortAddress* is set to 0xffff, the MLME will issue the MLME-START.confirm primitive with a status of NO_SHORT_ADDRESS.

When the CoordRealignment parameter is set to TRUE, the coordinator attempts to transmit a coordinator realignment command frame as described in 9.7.1.3. If the transmission of the coordinator realignment command fails due to a channel access failure, the MLME will not make any changes to the superframe configuration (i.e., no PIB attributes will be changed) and will issue an MLME-START.confirm with a status of CHANNEL_ACCESS_FAILURE. If the coordinator realignment command is successfully transmitted, the MLME updates the appropriate PIB parameters with the values of the BeaconOrder, SuperframeOrder, WPANId, ChannelPage, and LogicalChannel parameters, as described in 9.7.1.5, and will issue an MLME-START.confirm with a status of SUCCESS.

When the CoordRealignment parameter is set to FALSE, the MLME updates the appropriate PIB parameters with the values of the BeaconOrder, SuperframeOrder, WPANId, ChannelPage, and LogicalChannel parameters, as described in 9.7.1.5.

The address used by the coordinator in its beacon frames is determined by the current value of *macShortAddress*, which is set by the next higher layer before issuing this primitive.

If the SecurityLevel parameter is set to a valid value other than 0x00, indicating that security is required for this frame, the MLME will set the Security Enabled subfield of the Frame Control field to one. The MAC sublayer will perform outgoing processing on the frame, as described in 9.7.9.2.1. If the CoordRealignment parameter is set to TRUE, the CoordRealignSecurityLevel, CoordRealignKeyIdMode, CoordRealignKey-Source, and CoordRealignKeyIndex parameters will be used to process the MAC command frame. If the BeaconOrder parameter indicates a beacon-enabled network, the BeaconSecurityLevel, BeaconKeyIdMode, BeaconKeySource, and BeaconKeyIndex parameters will be used to process the beacon frame. If any error occurs during outgoing frame processing, the MLME will discard the frame and issue the MLME-START.confirm primitive with the error status returned by outgoing frame processing.

If the length of the beacon frame exceeds *aMaxPHYPacketSize* (e.g., due to the additional overhead required for security processing), the MAC sublayer shall discard the beacon frame and issue the MLME-START.confirm primitive with a status of FRAME_TOO_LONG.

The MLME shall ignore the StartTime parameter if the BeaconOrder parameter is equal to 15 because this indicates a nonbeacon-enabled VLC WPAN. If the BeaconOrder parameter is less than 15, the MLME examines the StartTime parameter to determine the time to begin transmitting beacons; the time is defined in symbols and is rounded to a backoff slot boundary. If the VLC coordinator parameter is set to TRUE, the MLME ignores the StartTime parameter and begins beacon transmissions immediately. Setting the StartTime parameter to 0x000000 also causes the MLME to begin beacon transmissions immediately. If the WPANCoordinator parameter is set to FALSE and the StartTime parameter is nonzero, the MLME calculates the beacon transmission time by adding StartTime symbols to the time, obtained from the local clock, when the MLME receives the beacon of the coordinator through which it is associated. If the time calculated causes the outgoing superframe to overlap the incoming superframe, the MLME shall not begin beacon transmissions. In this case, the MLME issues the MLME-START.confirm primitive with a status of SUPERFRAME_OVERLAP. Otherwise, the MLME then begins beacon transmissions when the current time, obtained from the local clock, equals the number of calculated symbols.

If the StartTime parameter is nonzero and the MLME is not currently tracking the beacon of the coordinator through which it is associated, the MLME will issue the MLME-START.confirm primitive with a status of TRACKING_OFF.

On completion of this procedure, the MLME responds with the MLME-START.confirm primitive. If the attempt to start using a new superframe configuration was successful, the status parameter will be set to SUCCESS. If any parameter is not supported or is out of range, the status parameter will be set to INVALID_PARAMETER.

7.1.13.2 MLME-START.confirm

The MLME-START.confirm primitive reports the results of the attempt to start using a new superframe configuration.

7.1.13.2.1 Semantics of the service primitive

The semantics of the MLME-START.confirm primitive are as follows:

```
MLME-START.confirm          (
                            status
                            )
```

Table 55 specifies the parameters for the MLME-START.confirm primitive.

Table 55—MLME-START.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, NO_SHORT_ADDRESS, SUPERFRAME_OVERLAP, TRACKING_OFF, INVALID_PARAMETER, COUNTER_ERROR, FRAME_TOO_LONG, UNAVAILABLE_KEY, UNSUPPORTED_SECURITY or CHANNEL_ACCESS_FAILURE	The result of the attempt to start using an updated superframe configuration.

7.1.13.2.2 When generated

The MLME-START.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-START.request primitive. The MLME-START.confirm primitive returns a status of either SUCCESS, indicating that the MAC sublayer has started using the new superframe configuration, or the appropriate error code. The status values are fully described in 7.1.13.1.3 and subclauses referenced by 7.1.13.1.3.

7.1.13.2.3 Appropriate usage

On receipt of the MLME-START.confirm primitive, the next higher layer is notified of the result of its request to start using a new superframe configuration. If the MAC sublayer has been successful, the status parameter will be set to SUCCESS. Otherwise, the status parameter indicates the error.

7.1.13.3 Message sequence chart for updating the superframe configuration

Figure 48 illustrates the sequence of messages necessary for initiating beacon transmissions in an FFD. Figure 133 (see 9.9) illustrates the sequence of messages necessary for the VLC coordinator to start beaconing on a new VLC WPAN; this figure includes steps taken by the PHY.

7.1.14 Primitives for synchronizing with a coordinator

MLME-SAP synchronization primitives define how synchronization with a coordinator may be achieved and how a loss of synchronization is communicated to the next higher layer.

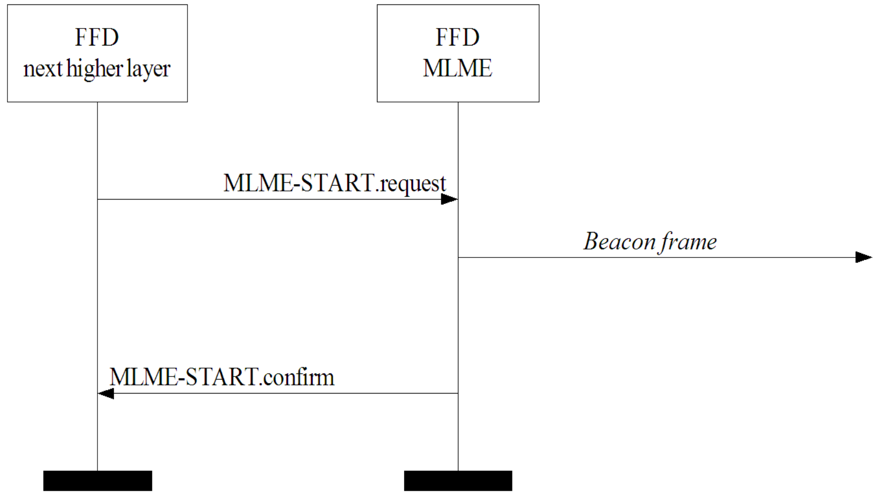


Figure 48—Message sequence chart for updating the superframe configuration

All devices shall provide an interface for the indication primitive. The request primitive is optional.

7.1.14.1 MLME-SYNC.request

The MLME-SYNC.request primitive requests to synchronize with the coordinator by acquiring and, if specified, tracking its beacons.

7.1.14.1.1 Semantics of the service primitive

The semantics of the MLME-SYNC.request primitive are as follows:

```
MLME-SYNC.request              (
                               LogicalChannel,
                               TrackBeacon
                               )
```

Table 56 specifies the parameters for the MLME-SYNC.request primitive.

Table 56—MLME-SYNC.request parameters

Name	Type	Valid range	Description
LogicalChannel	Integer	Selected from the available logical channels supported by the PHY	The logical channel on which to attempt coordinator synchronization.
TrackBeacon	Boolean	TRUE or FALSE	TRUE if the MLME is to synchronize with the next beacon and attempt to track all future beacons. FALSE if the MLME is to synchronize with only the next beacon.

7.1.14.1.2 Appropriate usage

The MLME-SYNC.request primitive is generated by the next higher layer of a device on a beacon-enabled VLC WPAN and issued to its MLME to synchronize with the coordinator.

7.1.14.1.3 Effect on receipt

If the MLME-SYNC.request primitive is received by the MLME on a beacon-enabled VLC WPAN, it will first set *phyCurrentPage* and *phyCurrentChannel* equal to the values of the ChannelPage and LogicalChannel parameters, respectively; both attributes are updated by issuing the PLME-SET.request primitive. If the TrackBeacon parameter is equal to TRUE, the MLME will track the beacon, i.e., enable its receiver just before the expected time of each beacon so that the beacon frame can be processed. If the TrackBeacon parameter is equal to FALSE, the MLME will locate the beacon, but not continue to track it.

If this primitive is received by the MLME while it is currently tracking the beacon, the MLME will not discard the primitive, but rather treat it as a new synchronization request.

If the beacon could not be located either on its initial search or during tracking, the MLME will issue the MLME-SYNC-LOSS.indication primitive with a loss reason of BEACON_LOST.

7.1.14.2 MLME-SYNC-LOSS.indication

The MLME-SYNC-LOSS.indication primitive indicates the loss of synchronization with a coordinator.

7.1.14.2.1 Semantics of the service primitive

The semantics of the MLME-SYNC-LOSS.indication primitive are as follows:

```
MLME-SYNC-LOSS.indication     (
                              LossReason,
                              WPANId,
                              LogicalChannel,
                              SecurityLevel,
                              KeyIdMode,
                              KeySource,
                              KeyIndex
                              )
```

Table 57 specifies the parameters for the MLME-SYNC-LOSS.indication primitive.

Table 57—MLME-SYNC-LOSS.indication parameters

Name	Type	Valid range	Description
LossReason	Enumeration	WPAN_ID_CONFLICT, REALIGNMENT, or BEACON_LOST	The reason that synchronization was lost.
WPANId	Integer	0x0000–0xffff	The WPAN identifier with which the device lost synchronization or to which it was realigned.

Table 57—MLME-SYNC-LOSS.indication parameters *(continued)*

Name	Type	Valid range	Description
LogicalChannel	Integer	Selected from the available logical channels supported by the PHY (see 6.1.2).	The logical channel on which the device lost synchronization or to which it was realigned.
SecurityLevel	Integer	0x00-0x07	If the primitive was either generated by the device itself following loss of synchronization or generated by the coordinator upon detection of a WPAN ID conflict, the security level is set to 0x00. If the primitive was generated following the reception of either a coordinator realignment command or a WPAN ID conflict notification command: The security level purportedly used by the received MAC frame (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	If the primitive was either generated by the device itself following loss of synchronization or generated by the coordinator upon detection of a WPAN ID conflict, this parameter is ignored. If the primitive was generated following the reception of either a coordinator realignment command or a WPAN ID conflict notification command: The mode used to identify the key purportedly used by the originator of the received frame (see Table 86 in 9.8.2.2.2). This parameter is invalid if the SecurityLevel parameter is set to 0x00.

Table 57—MLME-SYNC-LOSS.indication parameters *(continued)*

Name	Type	Valid range	Description
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	If the primitive was either generated by the device itself following loss of synchronization or generated by the coordinator upon detection of a WPAN ID conflict, this parameter is ignored. If the primitive was generated following the reception of either a coordinator realignment command or a WPAN ID conflict notification command: The originator of the key purportedly used by the originator of the received frame (see 9.8.2.4.1). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.
KeyIndex	Integer	0x01–0xff	If the primitive was either generated by the device itself following loss of synchronization or generated by the coordinator upon detection of a WPAN ID conflict, this parameter is ignored. If the primitive was generated following the reception of either a coordinator realignment command or a WPAN ID conflict notification command: The index of the key purportedly used by the originator of the received frame (see 9.8.2.4.2). This parameter is invalid if the KeyIdMode parameter is invalid or set to 0x00.

7.1.14.2.2 When generated

The MLME-SYNC-LOSS.indication primitive is generated by the MLME of a device and issued to its next higher layer in the event of a loss of synchronization with the coordinator. It is also generated by the MLME of the VLC coordinator and issued to its next higher layer in the event of a WPAN ID conflict.

If a device that is associated through the VLC coordinator has detected a WPAN identifier conflict and communicated it to the VLC coordinator, the MLME will issue this primitive with the LossReason parameter set to WPAN_ID_CONFLICT. Similarly, if the VLC coordinator receives a WPAN ID conflict notification command (see 7.4.5), the MLME will issue this primitive with the LossReason parameter set to WPAN_ID_CONFLICT.

If a device has received the coordinator realignment command (see 7.4.8) from the coordinator through which it is associated and the MLME was not carrying out an orphan scan, the MLME will issue this primitive with the LossReason parameter set to REALIGNMENT and the WPANId, LogicalChannel, ChannelPage, and security-related parameters set as described in 9.7.1.4.

If a device has not heard the beacon for *aMaxLostBeacons* consecutive superframes following an MLME-SYNC.request primitive, either initially or during tracking, the MLME will issue this primitive with the LossReason parameter set to BEACON_LOST. The WPANId, LogicalChannel and ChannelPage parameters shall be set according to the coordinator with which synchronization was lost. The SecurityLevel parameter shall be set to zero and the KeyIdMode, KeySource, and KeyIndex parameters shall be ignored. If the beacon was being tracked, the MLME will not attempt to track the beacon any further.

7.1.14.2.3 Appropriate usage

On receipt of the MLME-SYNC-LOSS.indication primitive, the next higher layer is notified of a loss of synchronization.

7.1.14.3 Message sequence chart for synchronizing with a coordinator

Figure 49 illustrates the sequence of messages necessary for a device to synchronize with a coordinator. In Figure 49a), a single synchronization request is issued. The MLME then searches for a beacon and, if found, determines whether the coordinator has any data pending for the device. If so, the data are requested as described in 9.7.7.3. In Figure 49b), a track synchronization request is issued. The MLME then searches for a beacon and, if found, attempts to keep track of it using a timer that expires just before the expected time of the next beacon.

For both examples Figure 49a) and Figure 49b), the received beacon frames do not contain payload, and *macAutoRequest* is set to TRUE. The MLME also checks for any data pending in the coordinator for the device when a beacon frame is received.

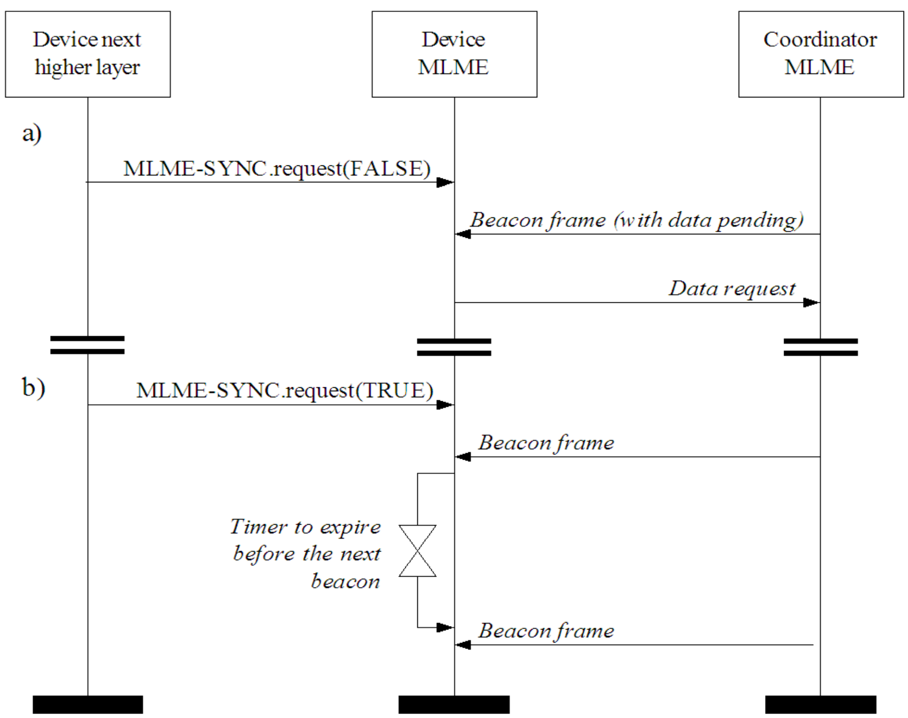


Figure 49—Message sequence chart for synchronizing to a coordinator in a beacon-enabled VLC WPAN

7.1.15 Primitives for requesting data from a coordinator

MLME-SAP polling primitives define how to request data from a coordinator.

All devices shall provide an interface for these polling primitives.

7.1.15.1 MLME-POLL.request

The MLME-POLL.request primitive prompts the device to request data from the coordinator.

7.1.15.1.1 Semantics of the service primitive

The semantics of the MLME-POLL.request primitive are as follows:

```
MLME-POLL.request          (
                           CoordAddrMode,
                           CoordWPANId,
                           CoordAddress,
                           SecurityLevel,
                           KeyIdMode,
                           KeySource,
                           KeyIndex
                           )
```

Table 58 specifies the parameter for the MLME-POLL.request primitive.

Table 58—MLME-POLL.request parameters

Name	Type	Valid range	Description
CoordAddrMode	Integer	0x02–0x03	The addressing mode of the coordinator to which the poll is intended. This parameter can take one of the following values: 2 = 16-bit short address, 3 = 64-bit extended address.
CoordWPANId	Integer	0x0000–0xfffe	The WPAN identifier of the coordinator to which the poll is intended.
CoordAddress	Device-Address	As specified by the CoordAddrMode parameter	The address of the coordinator to which the poll is intended.
SecurityLevel	Integer	0x00–0x07	The security level to be used (see Table 85 in 9.8.2.2.1).
KeyIdMode	Integer	0x00–0x03	The mode used to identify the key to be used (see Table 86 in 9.8.2.2.2). This parameter is ignored if the SecurityLevel parameter is set to 0x00.
KeySource	Set of 0, 4, or 8 octets	As specified by the KeyIdMode parameter	The originator of the key to be used (see 9.8.2.4.1). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.
KeyIndex	Integer	0x01–0xff	The index of the key to be used (see 9.8.2.4.2). This parameter is ignored if the KeyIdMode parameter is ignored or set to 0x00.

7.1.15.1.2 Appropriate usage

The MLME-POLL.request primitive is generated by the next higher layer and issued to its MLME when data are to be requested from a coordinator.

7.1.15.1.3 Effect on receipt

On receipt of the MLME-POLL.request primitive, the MLME generates and sends a data request command (see 7.4.4). If the poll is directed to the coordinator, the data request command may be generated without any destination address information present. Otherwise, the data request command is always generated with the destination address information in the CoordWPANId and CoordAddress parameters.

If the SecurityLevel parameter is set to a valid value other than 0x00, indicating that security is required for this frame, the MLME will set the Security Enabled subfield of the Frame Control field to one. The MAC sublayer will perform outgoing processing on the frame based on the CoordAddress, SecurityLevel, KeyIdMode, KeySource, and KeyIndex parameters, as described in 9.7.9.2.1. If any error occurs during outgoing frame processing, the MLME will discard the frame and issue the MLME-POLL.confirm primitive with the error status returned by outgoing frame processing.

If the data request command cannot be sent due to a random access algorithm failure, the MLME will issue the MLME-POLL.confirm primitive with a status of CHANNEL_ACCESS_FAILURE.

If the MLME successfully transmits a data request command, the MLME will expect an acknowledgment in return. If an acknowledgment is not received, the MLME will issue the MLME-POLL.confirm primitive with a status of NO_ACK (see 9.7.7.4).

If an acknowledgment is received, the MLME will request that the PHY enable its receiver if the Frame Pending subfield of the acknowledgment frame is set to one. If the Frame Pending subfield of the acknowledgment frame is set to zero, the MLME will issue the MLME-POLL.confirm primitive with a status of NO_DATA.

If a frame is received from the coordinator with a zero length payload or if the frame is a MAC command frame, the MLME will issue the MLME-POLL.confirm primitive with a status of NO_DATA. If a frame is received from the coordinator with nonzero length payload, the MLME will issue the MLME-POLL.confirm primitive with a status of SUCCESS. In this case, the actual data are indicated to the next higher layer using the MCPS-DATA.indication primitive (see 7.1.1.3).

If a frame is not received within *macMaxFrameTotalWaitTime* CAP symbols in a beacon-enabled VLC WPAN, or symbols in a nonbeacon-enabled VLC WPAN, even though the acknowledgment to the data request command has its Frame Pending subfield set to one, the MLME will issue the MLME-POLL.confirm primitive with a status of NO_DATA.

If any parameter in the MLME-POLL.request primitive is not supported or is out of range, the MLME will issue the MLME-POLL.confirm primitive with a status of INVALID_PARAMETER.

7.1.15.2 MLME-POLL.confirm

The MLME-POLL.confirm primitive reports the results of a request to poll the coordinator for data.

7.1.15.2.1 Semantics of the service primitive

The semantics of the MLME-POLL.confirm primitive are as follows:

```
MLME-POLL.confirm          (
                           status
                           )
```

Table 59 specifies the parameters for the MLME-POLL.confirm primitive.

Table 59—MLME-POLL.confirm parameters

Name	Type	Valid range	Description
status	Integer	SUCCESS, CHANNEL_ACCESS_FAILURE, NO_ACK, NO_DATA, COUNTER_ERROR, FRAME_TOO_LONG, UNAVAILABLE_KEY, UNSUPPORTED_SECURITY or INVALID_PARAMETER	The status of the data request.

7.1.15.2.2 When generated

The MLME-POLL.confirm primitive is generated by the MLME and issued to its next higher layer in response to an MLME-POLL.request primitive. If the request was successful, the status parameter will be equal to SUCCESS, indicating a successful poll for data. Otherwise, the status parameter indicates the appropriate error code. The status values are fully described in 7.1.15.1.3 and the subclauses referenced by 7.1.15.1.3.

7.1.15.2.3 Appropriate usage

On receipt of the MLME-POLL.confirm primitive, the next higher layer is notified of the status of the procedure to request data from the coordinator.

7.1.15.3 Message sequence chart for requesting data from a coordinator

Figure 50 illustrates the sequence of messages necessary, including the layer behavior of the device and the over-the-air interface, for a device to request data from a coordinator.

In both scenarios Figure 50a) and Figure 50b), a poll request is issued to the MLME, which then sends a data request command to the coordinator. In Figure 50a), the corresponding acknowledgment has the Frame Pending (FP) subfield set to zero and the MLME issues the poll request confirmation immediately. In Figure 50b), the corresponding acknowledgment has the Frame Pending subfield set to one and the MLME enables the receiver in anticipation of the data frame from the coordinator. On receipt of this data frame, the MLME issues a poll request confirmation followed by a data indication containing the data of the received frame.

7.1.16 Primitives for requesting dimmer settings from the DME

MLME-SAP dimmer primitives defines how to request dimmer data from a DME.

All devices shall provide an interface for these dimmer primitives.

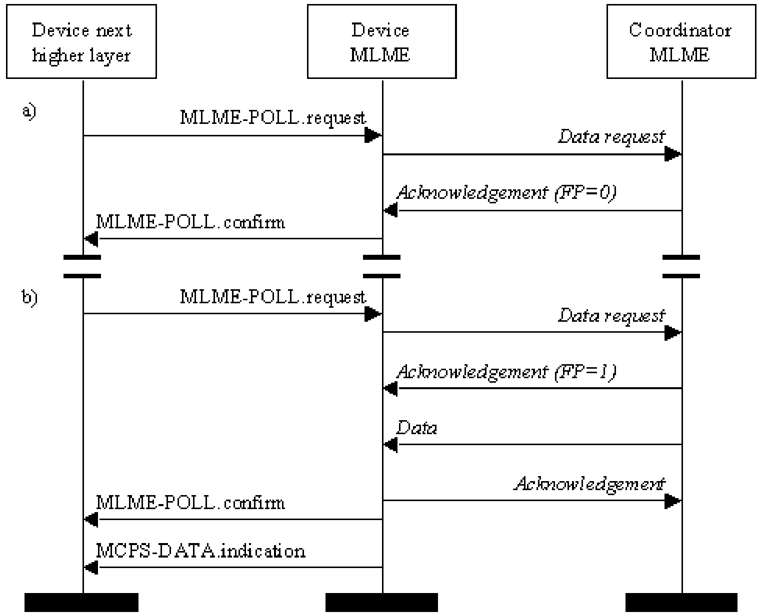


Figure 50—Message sequence chart for requesting data from the coordinator

(Ed. Note: Figure 25 needs to be modified for the DIMMER primitive)

7.1.16.1 MLME-DIMMER.request

The MLME-DIMMER.request primitive requests that the MLME perform the dimmer function as defined in x.x.x.

7.1.16.1.1 Semantics of the service primitive

The semantics of the PLME-DIMMER.request primitive is as follows:

MLME-DIMMER.request	(
	PIBDim
	PIBDimValue
	)

Table 14 specifies the parameters for the MLME-DIMMER.request primitive.

7.1.16.1.2 When generated

The MLME-DIMMER.request primitive is generated by the MLME and issued to its MLME whenever the dimmer algorithm requires the required dimming value.

Table 60—MLME-DIMMER.request parameters

Name	Type	Valid range	Description
PIBAttribute	Enumeration	See Table X	The identifier of the PIB attribute to set.
PIBAttributeValue	Various	Attribute specific	The value of the indicated PIB attribute to set.

7.1.16.1.3 Effect on receipt

If the transmitter is enabled on receipt of the MLME-DIMMER.request primitive, the MLME will cause the MAC to perform the required dimming function. When the MAC has completed the required dimming, the MLME will issue the MLME-DIMMER.confirm primitive with the status of COMPLETE.

7.1.16.2 MLME-DIMMER.confirm

The MLME-DIMMER.confirm primitive reports the results of a dimming request.

7.1.16.2.1 Semantics of the service primitive

The semantics of the MLME-DIMMER.confirm primitive is as follows:

```
MLME-DIMMER.confirm          (
                             status
                             )
```

Table 8 specifies the parameters for the MLME-DIMMER.confirm primitive.

Table 61—MLME-DIMMER.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	TRX_OFF, TX_ON, BUSY, or IDLE	The result of the request to perform a CCA.

7.1.16.2.2 When generated

The MLME-DIMMER.confirm primitive is generated by the MLME and issued to its MLME in response to a MLME-DIMMER.request primitive. The MLME-DIMMER.confirm primitive will return a status of either BUSY or IDLE, indicating a successful dimming. The reasons for these status values are fully described in 6.x.x.x.x.

7.1.16.2.3 Effect on receipt

On receipt of the MLME-DIMMER.confirm primitive, the MLME is notified of the results of the dimming. If the DIMMER attempt was successful, the status parameter is set to either BUSY or IDLE. Otherwise, the status parameter will indicate the error.

7.2 MAC frame formats

This subclause specifies the format of the MAC frame (MPDU). Each MAC frame consists of the following basic components:

a) A MHR, which comprises frame control, sequence number, address information, and security-related information.

b) A MAC payload, of variable length, which contains information specific to the frame type. Acknowledgment frames do not contain a payload.

c) A MFR, which contains a FCS.

The frames in the MAC sublayer are described as a sequence of fields in a specific order. All frame formats in this subclause are depicted in the order in which they are transmitted by the PHY, from left to right, where the leftmost bit is transmitted first in time. Bits within each field are numbered from 0 (leftmost and least significant) to $k - 1$ (rightmost and most significant), where the length of the field is k bits. Fields that are longer than a single octet are sent to the PHY in the order from the octet containing the lowest numbered bits to the octet containing the highest numbered bits.

For every MAC frame, all reserved bits shall be set to zero upon transmission and shall be ignored upon receipt.

7.2.1 General MAC frame format

The MAC frame format is composed of a MHR, a MAC payload, and a MFR. The fields of the MHR appear in a fixed order; however, the addressing fields may not be included in all frames. The general MAC frame shall be formatted as illustrated in Figure 51.

<table>
<tr><th>Octets: 2</th><th>1</th><th>0/2/8</th><th>0/2/8</th><th>0/2</th><th>0/2/8</th><th>0/5/6/10/14</th><th>variable</th><th>2</th></tr>
<tr><td rowspan="2">Frame Control</td><td rowspan="2">Sequence Number</td><td>Destination Address</td><td>Destination Address</td><td>Source WPAN Identifier</td><td>Source Address</td><td rowspan="2">Auxiliary Security Header</td><td rowspan="2">Frame Payload</td><td rowspan="2">FCS</td></tr>
<tr><td colspan="4">Addressing fields</td></tr>
<tr><td colspan="7">MHR</td><td>MAC Payload</td><td>MFR</td></tr>
</table>

Figure 51—General MAC frame format

7.2.1.1 Frame Control field

The Frame Control field is 2 octets in length and contains information defining the frame type, addressing fields, and other control flags. The Frame Control field shall be formatted as illustrated in Figure 52.

Bits: 0–2	3	4	5	6	7–9	10–11	12–13	14–15
Frame Type	Security Enabled	Frame Pending	Ack. Request	WPAN ID Compression	Reserved	Dest. Addressing Mode	Frame Version	Source Addressing Mode

Figure 52—Format of the Frame Control field

7.2.1.1.1 Frame Type subfield

The Frame Type subfield is 3 bits in length and shall be set to one of the nonreserved values listed in Table 62.

Table 62—Values of the Frame Type subfield

Frame type value b_2 b_1 b_0	Description
000	Beacon
001	Data
010	Acknowledgment
011	MAC command
100	Visibility
101–111	*Reserved*

7.2.1.1.2 Security Enabled subfield

The Security Enabled subfield is 1 bit in length, and it shall be set to one if the frame is protected by the MAC sublayer and shall be set to zero otherwise. The Auxiliary Security Header field of the MHR shall be present only if the Security Enabled subfield is set to one.

7.2.1.1.3 Frame Pending subfield

The Frame Pending subfield is 1 bit in length and shall be set to one if the device sending the frame has more data for the recipient. This subfield shall be set to zero otherwise (see 9.7.7.3).

The Frame Pending subfield shall be used only in beacon frames or frames transmitted either during the CAP by devices operating on a beacon-enabled VLC WPAN or at any time by devices operating on a nonbeacon-enabled VLC WPAN.

At all other times, it shall be set to zero on transmission and ignored on reception.

7.2.1.1.4 Acknowledgment Request subfield

The Acknowledgment Request subfield is 1 bit in length and specifies whether an acknowledgment is required from the recipient device on receipt of a data or MAC command frame. If this subfield is set to one, the recipient device shall send an acknowledgment frame only if, upon reception, the frame passes the third level of filtering (see 9.7.7.2). If this subfield is set to zero, the recipient device shall not send an acknowledgment frame.

7.2.1.1.5 WPAN ID Compression subfield

The WPAN ID Compression subfield is 1 bit in length and specifies whether the MAC frame is to be sent containing only one of the WPAN identifier fields when both source and destination addresses are present. If this subfield is set to one and both the source and destination addresses are present, the frame shall contain only the Destination WPAN Identifier field, and the Source WPAN Identifier field shall be assumed equal to that of the destination. If this subfield is set to zero and both the source and destination addresses are present, the frame shall contain both the Source WPAN Identifier and Destination WPAN Identifier fields. If only one of the addresses is present, this subfield shall be set to zero, and the frame shall contain the WPAN identifier field corresponding to the address. If neither address is present, this subfield shall be set to zero, and the frame shall not contain either WPAN identifier field.

7.2.1.1.6 Destination Addressing Mode subfield

The Destination Addressing Mode subfield is 2 bits in length and shall be set to one of the nonreserved values listed in Table 63.

If this subfield is equal to zero and the Frame Type subfield does not specify that this frame is an acknowledgment or beacon frame, the Source Addressing Mode subfield shall be nonzero, implying that the frame is directed to the VLC coordinator with the VLC WPAN identifier as specified in the Source WPAN Identifier field. If this subfield is equal to 01, the Source Addressing Mode subfield shall be equal to 01, implying that the frame is a broadcast frame, and no source or destination ad-dress fields are present in the frame.

Table 63—Possible values of the Destination Addressing Mode and Source Addressing Mode subfields

Addressing mode value b_1 b_0	Description
00	WPAN identifier and address fields are not present.
01	No address field (broadcast only mode with no address fields present).
10	Address field contains a 16-bit short address.
11	Address field contains a 64-bit extended address.

7.2.1.1.7 Frame Version subfield

The Frame Version subfield is 2 bits in length and specifies the version number corresponding to the frame.

This subfield shall be set to 0x00 to indicate a frame compatible with IEEE Std 802.15.7 and 0x01 to indicate an IEEE802.15.7 frame. All other subfield values shall be reserved for future use. See 7.2.3 for details on frame compatibility.

7.2.1.1.8 Source Addressing Mode subfield

The Source Addressing Mode subfield is 2 bits in length and shall be set to one of the nonreserved values listed in Table 63.

If this subfield is equal to zero and the Frame Type subfield does not specify that this frame is an acknowledgment frame, the Destination Addressing Mode subfield shall be nonzero, implying that the frame has originated from the coordinator with the WPAN identifier as specified in the Destination WPAN Identifier field.

If this subfield is equal to 01, the Source Addressing Mode subfield shall be equal to 01, implying that the frame is a broadcast frame, and no source or destination address fields are present in the frame.

7.2.1.2 Sequence Number field

The Sequence Number field is 1 octet in length and specifies the sequence identifier for the frame.

For a beacon frame, the Sequence Number field shall specify a BSN. For a data, acknowledgment, or MAC command frame, the Sequence Number field shall specify a DSN that is used to match an acknowledgment frame to the data or MAC command frame.

7.2.1.3 Destination WPAN Identifier field

The Destination WPAN Identifier field, when present, is 2 octets in length and specifies the unique WPAN identifier of the intended recipient of the frame. A value of 0xffff in this field shall represent the broadcast WPAN identifier, which shall be accepted as a valid WPAN identifier by all devices currently listening to the channel.

This field shall be included in the MAC frame only if the Destination Addressing Mode subfield of the Frame Control field is 10 or 11.

7.2.1.4 Destination Address field

The Destination Address field, when present, is either 2 octets or 8 octets in length, according to the value specified in the Destination Addressing Mode subfield of the Frame Control field (see 7.2.1.1.6), and specifies the address of the intended recipient of the frame. A 16-bit value of 0xffff in this field shall represent the broadcast short address, which shall be accepted as a valid 16-bit short address by all devices currently listening to the channel.

This field shall be included in the MAC frame only if the Destination Addressing Mode subfield of the Frame Control field is nonzero.

7.2.1.5 Source WPAN Identifier field

The Source WPAN Identifier field, when present, is 2 octets in length and specifies the unique WPAN identifier of the originator of the frame. This field shall be included in the MAC frame only if the Source Addressing Mode and WPAN ID Compression subfields of the Frame Control field are nonzero and equal to zero, respectively.

The WPAN identifier of a device is initially determined during association on a VLC WPAN, but may change following a VLC WPAN identifier conflict resolution (see 9.7.1).

7.2.1.6 Source Address field

The Source Address field, when present, is either 2 octets or 8 octets in length, according to the value specified in the Source Addressing Mode subfield of the Frame Control field (see 7.2.1.1.8), and specifies the address of the originator of the frame. This field shall be included in the MAC frame only if the Source Addressing Mode subfield of the Frame Control field is 10 or 11.

7.2.1.7 Auxiliary Security Header field

The Auxiliary Security Header field has a variable length and specifies information required for security processing, including how the frame is actually protected (security level) and which keying material from the MAC security PIB is used (see 9.8.1). This field shall be present only if the Security Enabled subfield is set to one. For details on formatting, see 9.8.2.

7.2.1.8 Frame Payload field

The Frame Payload field has a variable length and contains information specific to individual frame types. If the Security Enabled subfield is set to one in the Frame Control field, the frame payload is protected as defined by the security suite selected for that frame.

7.2.1.9 FCS field

The FCS field is 2 octets in length and contains a 16-bit ITU-T CRC. The FCS is calculated over the MHR and MAC payload parts of the frame.

The FCS shall be calculated using the following standard generator polynomial of degree 16:

$$G_{16}(x) = x^{16} + x^{12} + x^5 + 1 \qquad (1)$$

The FCS shall be calculated for transmission using the following algorithm:

— Let $M(x) = b_0x^{k-1} + b_1x^{k-2} + \ldots + b_{k-2}x + b_{k-1}$ be the polynomial representing the sequence of bits for which the checksum is to be computed.

— Multiply $M(x)$ by x^{16}, giving the polynomial $x^{16} \times M(x)$.

— Divide $x^{16} \times M(x)$ modulo 2 by the generator polynomial, $G_{16}(x)$, to obtain the remainder polynomial, $R(x) = r_0x^{15} + r_1x^{14} + \ldots + r_{14}x + r_{15}$.

— The FCS field is given by the coefficients of the remainder polynomial, *R(x)*.

Here, binary polynomials are represented as bit strings, in highest polynomial degree first order.

As an example, consider an acknowledgment frame with no payload and the following 3 byte MHR:

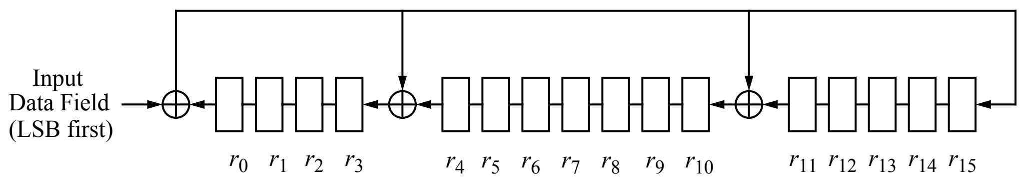
0100 0000 0000 0000 0101 0110 [leftmost bit (b_0) transmitted first in time]
b_0..b_{23}

The FCS for this case would be the following:

0010 0111 1001 1110 [leftmost bit (r_0) transmitted first in time]
r_0.............................r_{15}

A typical implementation is depicted in Figure 53.

CRC-16 Generator Polynomial: $G(x) = x^{16} + x^{12} + x^5 + 1$



1. Initialize the remainder register (r_0 through r_{15}) to zero.
2. Shift MHR and payload into the divider in the order of transmission (LSB first).
3. After the last bit of the data field is shifted into the divider, the remainder register contains the FCS.
4. The FCS is appended to the data field so that r_0 is transmitted first.

Figure 53—Typical FCS implementation

7.2.2 Format of individual frame types

Four frame types are defined: beacon, data, acknowledgment, and MAC command. These frame types are discussed in 7.2.2.1 through 7.2.2.6.

7.2.2.1 Beacon frame format

The beacon frame shall be formatted as illustrated in Figure 54.

Octets: 2	1	4/10	0/5/6/10/14	2	variable	variable	variable	2
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	Superframe Specification	GTS fields (Figure 55)	Pending address fields (Figure 56)	Beacon Payload	FCS
MHR				MAC Payload				MFR

Figure 54—Beacon frame format

The GTS fields shall be formatted as illustrated in Figure 55, and the pending address fields shall be formatted as illustrated in Figure 56.

Octets: 1	0/1	variable
GTS Specification	GTS Directions	GTS List

Figure 55—Format of the GTS information fields

Octets: 1	variable
Pending Address Specification	Address List

Figure 56—Format of the pending address information fields

The order of the fields of the beacon frame shall conform to the order of the general MAC frame as illustrated in Figure 51.

7.2.2.1.1 Beacon frame MHR fields

The MHR for a beacon frame shall contain the Frame Control field, the Sequence Number field, the Source WPAN Identifier field, and the Source Address field.

In the Frame Control field, the Frame Type subfield shall contain the value that indicates a beacon frame, as shown in Table 62, and the Source Addressing Mode subfield shall be set as appropriate for the address of the coordinator transmitting the beacon frame. If protection is used for the beacon, the Security Enabled subfield shall be set to one. The Frame Version subfield shall be set to one only if the Security Enabled subfield is set to one. If a broadcast data or command frame is pending, the Frame Pending subfield shall be set to one. All other subfields shall be set to zero and ignored on reception.

The Sequence Number field shall contain the current value of *macBSN*.

The addressing fields shall comprise only the source address fields. The Source WPAN Identifier and Source Address fields shall contain the WPAN identifier and address, respectively, of the device transmitting the beacon.

The Auxiliary Security Header field, if present, shall contain the information required for security processing of the beacon frame, as specified in 7.2.1.7.

7.2.2.1.2 Superframe Specification field

The Superframe Specification field is 16 bits in length and shall be formatted as illustrated in Figure 57.

Bits: 0–3	4-7	8-11	12	13	14	15
Beacon Order	Superframe Order	Final CAP Slot	Battery Life Extension (BLE)	Reserved	WPAN Coordinator	Association Permit

Figure 57—Format of the Superframe Specification field

The Beacon Order subfield is 4 bits in length and shall specify the transmission interval of the beacon. See 7.7.1.1 for an explanation of the relationship between the beacon order and the beacon interval.

The Superframe Order subfield is 4 bits in length and shall specify the length of time during which the superframe is active (i.e., receiver enabled), including the beacon frame transmission time. See 7.7.1.1 for an explanation of the relationship between the superframe order and the superframe duration.

The Final CAP Slot subfield is 4 bits in length and specifies the final superframe slot utilized by the CAP. The duration of the CAP, as implied by this subfield, shall be greater than or equal to the value specified by *aMinCAPLength*. However, an exception is allowed for the accommodation of the temporary increase in the beacon frame length needed to perform GTS maintenance (see 7.2.2.1.3).

The Battery Life Extension (BLE) subfield is 1 bit in length and shall be set to one if frames transmitted to the beaconing device during its CAP are required to start in or before *macBattLifeExtPeriods* full backoff periods after the IFS period following the beacon. Otherwise, the BLE subfield shall be set to zero.

The WPAN Coordinator subfield is 1 bit in length and shall be set to one if the beacon frame is being transmitted by the coordinator. Otherwise, the WPAN Coordinator subfield shall be set to zero.

The Association Permit subfield is 1 bit in length and shall be set to one if *macAssociationPermit* is set to TRUE (i.e., the coordinator is accepting association to the VLC WPAN). The association permit bit shall be set to zero if the coordinator is currently not accepting association requests on its network.

7.2.2.1.3 GTS Specification field

The GTS Specification field is 8 bits in length and shall be formatted as illustrated in Figure 58.

Bits: 0-2	3-6	7
GTS Descriptor Count	Reserved	GTS Permit

Figure 58—Format of the GTS Specification field

The GTS Descriptor Count subfield is 3 bits in length and specifies the number of 3-octet GTS descriptors contained in the GTS List field of the beacon frame. If the value of this subfield is greater than zero, the size of the CAP shall be allowed to dip below *aMinCAPLength* to accommodate the temporary increase in the beacon frame length caused by the inclusion of the subfield. If the value of this subfield is zero, the GTS Directions field and GTS List field of the beacon frame are not present.

The GTS Permit subfield is 1 bit in length and shall be set to one if *macGTSPermit* is equal to TRUE (i.e., the coordinator is accepting GTS requests). Otherwise, the GTS Permit field shall be set to zero.

7.2.2.1.4 GTS Directions field

The GTS Directions field is 8 bits in length and shall be formatted as illustrated in Figure 59.

Bits: 0-6	7
GTS Directions Mask	Reserved

Figure 59—Format of the GTS Directions field

The GTS Directions Mask subfield is 7 bits in length and contains a mask identifying the directions of the GTSs in the superframe. The lowest bit in the mask corresponds to the direction of the first GTS contained in the GTS List field of the beacon frame, with the remainder appearing in the order that they appear in the list. Each bit shall be set to one if the GTS is a receive-only GTS or to zero if the GTS is a transmit-only GTS. GTS direction is defined relative to the direction of the data frame transmission by the device.

7.2.2.1.5 GTS List field

The size of the GTS List field is defined by the values specified in the GTS Specification field of the beacon frame and contains the list of GTS descriptors that represents the GTSs that are being maintained. The maximum number of GTS descriptors shall be limited to seven.

Each GTS descriptor is 24 bits in length and shall be formatted as illustrated in Figure 60.

Bits: 0-15	16-19	20-23
Device Short Address	GTS Starting Slot	GTS Length

Figure 60—Format of the GTS descriptor

The Device Short Address subfield is 16 bits in length and shall contain the short address of the device for which the GTS descriptor is intended.

The GTS Starting Slot subfield is 4 bits in length and contains the superframe slot at which the GTS is to begin.

The GTS Length subfield is 4 bits in length and contains the number of contiguous superframe slots over which the GTS is active.

7.2.2.1.6 Pending Address Specification field

The Pending Address Specification field shall be formatted as illustrated in Figure 61.

Bits: 0-2	3	4-6	7
Number of Short Addresses Pending	Reserved	Number of Extended Addresses Pending	Reserved

Figure 61—Format of the Pending Address Specification field

The Number of Short Addresses Pending subfield is 3 bits in length and indicates the number of 16-bit short addresses contained in the Address List field of the beacon frame.

The Number of Extended Addresses Pending subfield is 3 bits in length and indicates the number of 64-bit extended addresses contained in the Address List field of the beacon frame.

7.2.2.1.7 Address List field

The size of the Address List field is determined by the values specified in the Pending Address Specification field of the beacon frame and contains the list of addresses of the devices that currently have messages pending with the coordinator. The address list shall not contain the broadcast short address 0xffff.

The maximum number of addresses pending shall be limited to seven and may comprise both short and extended addresses. All pending short addresses shall appear first in the list followed by any extended addresses. If the coordinator is able to store more than seven transactions, it shall indicate them in its beacon on a first-come-first-served basis, ensuring that the beacon frame contains at most seven addresses.

7.2.2.1.8 Beacon Payload field

The Beacon Payload field is an optional sequence of up to *aMaxBeaconPayloadLength* octets specified to be transmitted in the beacon frame by the next higher layer. The set of octets contained in *macBeaconPayload* shall be copied into this field. Information elements are included in the beacon frame. The information elements can also be transmitted separately for non-beacon modes using the management frames. These information elements include MAC capabilities IE, PHY capabilities IE, and channel change IE, identification IE.

(Table 1) MAC capabilities IE:

octets: 1	1	2	X
Element ID	Length (=2+X)	MAC Capability Bitmap	Reserved

MAC capabilities include

¢ Uni-directional traffic support

¢ Bi-directional traffic support

¢ P2P support

¢ P2MP support

¢ Visibility/Dimming support

(Table 1) MAC capabilities

Bit	Attribute	Description
0	Traffic support	0 = unidirectional (broadcast only) 1 = bi-directional
1-2	Topology	00 = reserved 10 = P2P only 01 = P2MP support 11 = both
3-4	Device type	00 = infrastructure 01 = mobile 10 = vehicle 11 = reserved
5	Beacon capability	1 = capable
6	Visibility support	1= support
7	Dimming support	1 = support
8	Co-ordinator support	1 = support, can act as co-ordinator for VLAN
9 - 15	Reserved	

7.2.2.2 Device type indication:

There is a need to indicate device type in the MAC capabilities IE. There are unique requirements for an infrastructure, such as continuous illumination vs. a mobile phone. It is not power efficient for a mobile phone to maintain continuous visibility. Mentioning the device type in the MAC capabilities provides knowledge of the requirements that that particular device needs to meet. This field is set by the upper layers when the device is being configured (dynamically) or deployed (statically).

(Table 1) Changes in PHY capabilities IE

octets: 1	1	2	X
Element ID	Length (=2+X)	PHY Capability Bitmap	Reserved

PHY capabilities include

- ¢ Number of distinct optical source types
- ¢ Number of leds per optical source type
- ¢ Aggregate channel support on per optical source basis (includes bandplan support)
- ¢ Guard channel support on per distinct optical source type basis
- ¢ Supported data rates
- ¢ Multi-direction support

(Table 1) PHY capabilities

Bit	Attribute	Description
0-2	Number of optical source types (n)	(n) Number of leds that are distinct (different colors)
3-5	Multi-direction support	Number of directions supported by device
6-15	Number of leds per optical source type	If > 1023 leds, use 1023 as the number.
8*n	Aggregate channels	See below
8*n	Guard channels	See below
8	Supported data rates	Includes low rate and high rate PHY modes

7.2.2.3 Aggregation and guard channel indication in PHY capabilities IE:

The aggregation and guard channels are used to support any visible light optical source for VLC that may have variable spectral widths and center frequencies. The aggregation and guard channels are indicated via an 8-bit bitmap, where every bit is indexed by the bandplan identification number. The bit position 'm' is set to a '1' for band 'm', if that band is in use. The aggregation bitmap also provides information on the band use for the current optical source type.

(Table 1) The aggregation bitmap

Bit 0	Bit 1	Bit 2	Bit 3	Bit 4	Bit 5	Bit 6	Bit 7
Band 0	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Reserved

For example,

if band 1 and band 2 needs to be aggregated (for a blue LED) the aggregation bit-map is indicated as 0110000 and the guard bit-map is indicated as 0000000.

if band 1 is being used but there is leakage in bands 3, 4, 5 (white LED : blue LED with yellow phosphor), the aggregation bit map is indicated as 0100000 and the guard bit-map is indicated as 0001110.

The reserved bit shall be set to 0.

7.2.2.4 Data frame format

The data frame shall be formatted as illustrated in Figure 62.

Octets: 2	1	(see 7.2.2.4.1)	0/5/6/10/14	variable	2
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	Data Payload	FCS
MHR				MAC Payload	MFR

Figure 62—Data frame format

The order of the fields of the data frame shall conform to the order of the general MAC frame as illustrated in Figure 51.

7.2.2.4.1 Data frame MHR fields

The MHR for a data frame shall contain the Frame Control field, the Sequence Number field, the destination WPAN identifier/address fields, and/or the source WPAN identifier/address fields.

In the Frame Control field, the Frame Type subfield shall contain the value that indicates a data frame, as shown in Table 62. If protection is used for the data, the Security Enabled subfield shall be set to one. The Frame Version subfield shall be set to one if either the Security Enabled subfield is set to one or the MAC Payload field is greater than *aMaxMACSafePayloadSize*. All other subfields shall be set appropriately according to the intended use of the data frame. All reserved subfields shall be set to zero and ignored on reception.

The Sequence Number field shall contain the current value of *macDSN*.

The addressing fields shall comprise the destination address fields and/or the source address fields, dependent on the settings in the Frame Control field.

The Auxiliary Security Header field, if present, shall contain the information required for security processing of the data frame, as specified in 7.2.1.7.

7.2.2.4.2 Data Payload field

The payload of a data frame shall contain the sequence of octets that the next higher layer has requested the MAC sublayer to transmit. The data type field is 1 byte and is explained in table below.

Table 64—Data Payload Field

Bits 0-1	Bits 2-7
00 – Single 01 – Packed 10 – Burst 11 - Reserved	Num PDUs per data frame

The data type field mentions the format used for sending the data - single, packed or burst. It also mentions the number of PDUs that are associated for this data frame.

The payload of a data frame shall contain the sequence of octets that the next higher layer has requested the MAC sub layer to transmit.

7.2.2.5 Acknowledgment frame format

The acknowledgment frame shall be formatted as illustrated in Figure 63.

Octets: 2	1	2
Frame Control	Sequence Number	FCS
MHR		MFR

Figure 63—Acknowledgment frame format

The order of the fields of the acknowledgment frame shall conform to the order of the general MAC frame as illustrated in Figure 51.

In B-ACK frames, the DestAddr field is set to the SrcAddr of the frame that requested the B-ACK. The B-ACK frame acknowledges correct or incorrect receipt of the previous sequence of frames and provides information for the transmission of the next sequence of frames as described in 17.8.3. The B-ACK frame payload is defined in Figure 45.

octets: 2	1	1	2	0-n
Buffer Size	Frame Count	Reserved	Sequence Control	Frame Bitmap

(Figure 1) B-ACK frame payload

The Buffer Size field specifies the maximum number of octets in the sum of the frame payloads of all frames in the next B-ACK sequence. The Frame Count field specifies the maximum number of frames in the next B-ACK sequence. The Sequence Control and Frame Bitmap fields together specify an acknowledgement window of MSDU fragments and their reception status. The Sequence Control field specifies the Sequence Number and Fragment Number that start the acknowledgement window.

bits: b15-14	b13-b3	b2-b0
Reserved	Sequence Number	Fragment Number

(Figure 1) B- ACK frame bitmap

The Frame Bitmap field varies in length. A zero-length Frame Bitmap field indicates an acknowledgement window of length zero. Otherwise, the least-significant octet of the Frame Bitmap field corresponds to the MSDU indicated by the Sequence Control field, and each bit of the octet corresponds to a fragment of that MSDU. The least-significant bit in each octet corresponds to the first fragment and successive bits correspond to successive fragments. Successive octets present in the Frame Bitmap field correspond to successive MSDUs, and each bit corresponds to a fragment of the MSDU. The acknowledgement window ends at fragment seven of the MSDU that corresponds to the most-significant octet in the Frame Bitmap. For all bits within the Frame Bitmap, a value of ONE indicates that the corresponding fragment was received in either the current sequence or an earlier one. A value of ZERO indicates that the corresponding fragment was not received in the current sequence (although it may have been received in an earlier one). Bits of the least-significant octet of the Frame Bitmap field corresponding to fragments prior to the start of the acknowledgement window are undefined. Frames with a Sequence Number earlier than the Sequence Number indicated in the Sequence Control field were not received in the last B-ACK sequence. Such frames were previously received or are no longer expected.

The block ACK is applicable to the packed data type. The bitmap and sequence number is repeated for every frame in the burst mode (multiple frames)

The order of the fields of the acknowledgment frame shall conform to the order of the general MAC frame as illustrated.

7.2.2.5.1 Acknowledgment frame MHR fields

The MHR for an acknowledgment frame shall contain only the Frame Control field and the Sequence Number field.

In the Frame Control field, the Frame Type subfield shall contain the value that indicates an acknowledgment frame, as shown in Table 62. If the acknowledgment frame is being sent in response to a received data request command, the device sending the acknowledgment frame shall determine whether it has data pending for the recipient. If the device can determine this before sending the acknowledgment frame (see 9.7.7.4.2), it shall set the Frame Pending subfield according to whether there is pending data. Otherwise, the Frame Pending subfield shall be set to one. If the acknowledgment frame is being sent in response to either a data frame or another type of MAC command frame, the device shall set the Frame Pending subfield to zero. All other subfields shall be set to zero and ignored on reception.

The Sequence Number field shall contain the value of the sequence number received in the frame for which the acknowledgment is to be sent.

7.2.2.6 MAC command frame format

The MAC command frame shall be formatted as illustrated in Figure 64.

Octets: 2	1	(see 7.2.2.6.1)	0/5/6/10/14	1	variable	2
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	Command Frame Identifier	Command Payload	FCS
MHR				MAC Payload		MFR

Figure 64—MAC command frame format

The order of the fields of the MAC command frame shall conform to the order of the general MAC frame as illustrated in Figure 51.

7.2.2.6.1 MAC command frame MHR fields

The MHR for a MAC command frame shall contain the Frame Control field, the Sequence Number field, the destination WPAN identifier/address fields and/or the source WPAN identifier/address fields.

In the Frame Control field, the Frame Type subfield shall contain the value that indicates a MAC command frame, as shown in Table 62. If the frame is to be secured, the Security Enabled subfield of the Frame Control field shall be set to one and the frame secured according to the process described in 9.7.9.1.3. Otherwise the Security Enabled subfield of the Frame Control field shall be set to zero. All other subfields shall be set appropriately according to the intended use of the MAC command frame. All reserved subfields shall be set to zero and ignored on reception.

The Sequence Number field shall contain the current value of *macDSN*.

The addressing fields shall comprise the destination address fields and/or the source address fields, dependent on the settings in the Frame Control field.

The Auxiliary Security Header field, if present, shall contain the information required for security processing of the MAC command frame, as specified in 7.2.1.7.

7.2.2.6.2 Command Frame Identifier field

The Command Frame Identifier field identifies the MAC command being used. This field shall be set to one of the nonreserved values listed in Table 66.

7.2.2.6.3 Command Payload field

The Command Payload field contains the MAC command itself. The formats of the individual commands are described in 7.4.

7.3 Information elements

The information elements are listed in Table XX. Individual elements are described in the following subclauses.

Table 65—Information Elements

Element ID hex value	Element	Subclause	Present in beacon
0x00	Codeword	7.4.1	TBD

The format of an individual IE is shown in Figure XX. The first octet is the Element ID and the second octet is the Length (Ln) of the payload of the IE in octets. The following Ln octets are the payload for the IE. Unless otherwise specified, these elements may appear in any order in the frames that are allowed to include more than one of these elements.

Figure 65—Information element format

octets: Ln	1	1
IE payload	Length (=Ln)	Element ID

7.3.1 Codeword

The Codeword IE shall be formatted as illustrated in Figure XX.

For this Codeword IE, one of 64 orthogonal sixteen bit codewords is assigned. These sixteen bit codewords can be generated by the following tables and procedure.

64 16 bit codewords for the Codeword IE can be formed as shown in FigX. These codewords are formed by cascading two identical 8-bit orthogonal codes. Received data sequence is divided into two subcodewords. Each subcodeword is compared with 8 8-bit codewords. 64 combinations of codewords can be realized. Therefore up to 64 devices can be associated to a network.

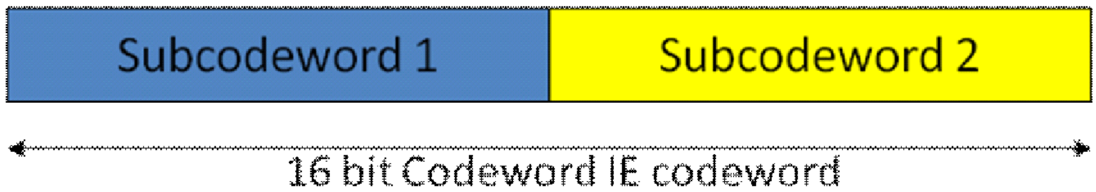


Figure 66—Cascading two identical codes to generate 16 bit codewords

For each subcodeword, the following table shown in Fig. is applied to form 16 bit codewords for Codeword IE codewords.

For subcodeword 1

RTS/ACK index	r0	r1	r2	r3	r4	r5	r6	r7
1	0	0	0	0	0	0	0	0
2	0	1	0	1	0	1	0	1
3	0	0	1	1	0	0	1	1
4	0	1	1	0	0	1	1	0
5	0	0	0	0	1	1	1	1
6	0	1	0	1	1	0	1	0
7	0	0	1	1	1	1	0	0
8	0	1	1	0	1	0	0	1

For subcodeword 2

RTS/ACK index	r8	r9	r10	r11	r12	r13	r14	r15
1	0	0	0	0	0	0	0	0
2	0	1	0	1	0	1	0	1
3	0	0	1	1	0	0	1	1
4	0	1	1	0	0	1	1	0
5	0	0	0	0	1	1	1	1
6	0	1	0	1	1	0	1	0
7	0	0	1	1	1	1	0	0
8	0	1	1	0	1	0	0	1

Any device who wants to be associated to a VLC WPAN selects one of 64 combinations of codewords randomly and sends it in the Codeword IE field of the Association Request command. If the coordinator receives this request and decides to allow this device to be associated with the VLC WPAN, it will send the same codeword that it received from that device to notify that this device is allowed to be associated with the network. If more than one device send request of association simultaneously, the coordinator selects one of them and sends exactly the same codeword among 64 combinations that was sent by the selected device in the Codeword IE of the Association Response command to notify that this device is allowed to be associated with the network. If more than one device selects the same codeword among 64 combinations with the same destination address and with different source address, collision occurs and random back-off algorithm is applied by resending request commands with random back-offs.

7.4 MAC command frames

The command frames defined by the MAC sublayer are listed in Table 66. An FFD shall be capable of transmitting and receiving all command frame types, with the exception of the GTS request command, while the requirements for an RFD are indicated by an "X" in the table. MAC commands shall only be transmitted in the CAP for beacon-enabled WPANs or at any time for nonbeacon-enabled WPANs.

How the MLME shall construct the individual commands for transmission is detailed in 7.4.1 through 7.4.13. MAC command reception shall abide by the procedure described in 9.7.7.2.

Table 66—MAC command frames

Command frame identifier	Command name	RFD		Subclause
		Tx	Rx	
0x01	Association request	X		7.4.1
0x02	Association response		X	7.4.2
0x03	Disassociation notification	X	X	7.4.3
0x04	Data request	X		7.4.4
0x05	WPAN ID conflict notification	X		7.4.5
0x06	Orphan notification	X		7.4.6
0x07	Beacon request			7.4.7
0x08	Coordinator realignment		X	7.4.8
0x09	GTS request			7.4.9
0x0a	Blinking notification			7.4.10
0x0b	Dimming notification			7.4.11
0x0c	Fast link recovery signaling			7.7.6
0x0d	Mobility notification			7.4.12
0x0e	Information element exchange			???
0x0f–0xff	Reserved			—

7.4.1 Association request command

The association request command allows a device to request association with a WPAN through the coordinator or a coordinator.

This command shall only be sent by an unassociated device that wishes to associate with a WPAN. A device shall only associate with a WPAN through the coordinator or a coordinator allowing association, as determined through the scan procedure.

All devices shall be capable of transmitting this command, although an RFD is not required to be capable of receiving it.

The association request command shall be formatted as illustrated in Figure 67.

octets: (see 7.2.2.6)	1	1	2
MHR fields	Command Frame Identifier (see Table 66)	Capability Information	Codeword IE

Figure 67—Association request command format

7.4.1.1 MHR fields

The Source Addressing Mode subfield of the Frame Control field shall be set to three (64-bit extended addressing). The Destination Addressing Mode subfield shall be set to the same mode as indicated in the beacon frame to which the association request command refers.

The Frame Pending subfield of the Frame Control field shall be set to zero and ignored upon reception, and the Acknowledgment Request subfield shall be set to one.

The Destination WPAN Identifier field shall contain the identifier of the VLC WPAN to which to associate. The Destination Address field shall contain the address from the beacon frame that was transmitted by the coordinator to which the association request command is being sent. The Source WPAN Identifier field shall contain the broadcast WPAN identifier (i.e., 0xffff). The Source Address field shall contain the value of *aExtendedAddress*.

7.4.1.2 Capability Information field

The Capability Information field shall be formatted as illustrated in Figure 68.

bits: 0	1	2	3	4-5	6	7
Alternate WPAN Coordinator	Device Type	Power Source	Receiver On When Idle	Reserved	Security Capability	Allocate Address

Figure 68—Capability Information field format

The Alternate WPAN Coordinator subfield is 1 bit in length and shall be set to one if the device is capable of becoming the coordinator. Otherwise, the Alternate WPAN Coordinator subfield shall be set to zero.

The Device Type subfield is 1 bit in length and shall be set to one if the device is an FFD. Otherwise, the Device Type subfield shall be set to zero to indicate an RFD.

The Power Source subfield is 1 bit in length and shall be set to one if the device is receiving power from the alternating current mains. Otherwise, the Power Source subfield shall be set to zero.

The Receiver On When Idle subfield is 1 bit in length and shall be set to one if the device does not disable its receiver to conserve power during idle periods. Otherwise, the Receiver On When Idle subfield shall be set to zero.

The Battery information subfield is 2 bits in length. It is set to reserved (11) if power source to 1.

Table 67—Battery Indication

Bits	Battery indication
00	unknown
01	< 50% (low battery)
10	>= 50% (sufficient battery)
11	reserved

The Security Capability subfield is 1 bit in length and shall be set to one if the device is capable of sending and receiving cryptographically protected MAC frames as specified in 9.7.9.2; it shall be set to zero otherwise.

The Allocate Address subfield is 1 bit in length and shall be set to one if the device wishes the coordinator to allocate a 16-bit short address as a result of the association procedure. Otherwise, it shall be set to zero.

7.4.1.3 Codeword IE

For this Codeword IE, one of 64 orthogonal sixteen bit codewords is assigned. These sixteen bit codewords can be generated by the same procedure as in 7.3.1. Operational procedure is also described in 7.3.1.3.

7.4.2 Association response command

The association response command allows the coordinator or a coordinator to communicate the results of an association attempt back to the device requesting association.

This command shall only be sent by the coordinator or coordinator to a device that is currently trying to associate.

All devices shall be capable of receiving this command, although an RFD is not required to be capable of transmitting it.

The association response command shall be formatted as illustrated in Figure 69.

octets: (see 7.2.2.6)	1	2	1	2
MHR fields	Command Frame Identifier (see Table 66)	Short Address	Association Status	Codeword IE

Figure 69—Association response command format

7.4.2.1 MHR fields

The Destination Addressing Mode and Source Addressing Mode subfields of the Frame Control field shall each be set to three (i.e., 64-bit extended addressing).

The Frame Pending subfield of the Frame Control field shall be set to zero and ignored upon reception, and the Acknowledgment Request subfield shall be set to one.

The WPAN ID Compression subfield of the Frame Control field shall be set to one. In accordance with this value of the WPAN ID Compression subfield, the Destination WPAN Identifier field shall contain the value of *macWPANId*, while the Source WPAN Identifier field shall be omitted. The Destination Address field shall contain the extended address of the device requesting association. The Source Address field shall contain the value of *aExtendedAddress*.

7.4.2.2 Short Address field

If the coordinator was not able to associate this device to its WPAN, the Short Address field shall be set to 0xffff, and the Association Status field shall contain the reason for the failure. If the coordinator was able to associate the device to its WPAN, this field shall contain the short address that the device may use in its communications on the WPAN until it is disassociated.

A Short Address field value equal to 0xfffe shall indicate that the device has been successfully associated with a WPAN, but has not been allocated a short address. In this case, the device shall communicate on the WPAN using only its 64-bit extended address.

7.4.2.3 Association Status field

The Association Status field shall contain one of the nonreserved values listed in Table 68.

Table 68—Valid values of the Association Status field

Association status	Description
0x00	Association successful.
0x01	WPAN at capacity.
0x02	WPAN access denied.
0x03–0x7f	Reserved.
0x80–0xff	Reserved for MAC primitive enumeration values.

7.4.2.4 Codeword IE

For this Codeword IE, one of 64 orthogonal sixteen bit codewords is assigned. These sixteen bit codewords can be generated by the same procedure as in 7.3.1. Operational procedure is also described in 7.3.1.3.

7.4.3 Disassociation notification command

The VLC coordinator, a coordinator, or an associated device may send the disassociate notification command.

All devices shall implement this command.

The disassociation notification command shall be formatted as illustrated in Figure 70.

octets: (see 7.2.2.6)	**1**	**1**
MHR fields	Command Frame Identifier (see Table 66)	Disassociation Reason

Figure 70—Disassociation notification command format

7.4.3.1 MHR fields

The Destination Addressing Mode subfield of the Frame Control field shall be set according to the addressing mode specified by the corresponding primitive. The Source Addressing Mode subfield shall be set to three (i.e., 64-bit extended addressing).

The Frame Pending subfield of the Frame Control field shall be set to zero and ignored upon reception, and the Acknowledgment Request subfield shall be set to one.

The WPAN ID Compression subfield of the Frame Control field shall be set to one. In accordance with this value of the WPAN ID Compression subfield, the Destination WPAN Identifier field shall contain the value of *macWPANId*, while the Source WPAN Identifier field shall be omitted. If the coordinator wants an associated device to leave the WPAN, then the Destination Address field shall contain the address of the device being removed from the WPAN. If an associated device wants to leave the VLC WPAN, then the Destination Address field shall contain the value of either *macCoordShortAddress*, if the Destination Addressing Mode subfield is equal to two, or *macCoordExtendedAddress*, if the Destination Addressing Mode subfield is equal to three. The Source Address field shall contain the value of *aExtendedAddress*.

7.4.3.2 Disassociation Reason field

The Disassociation Reason field shall contain one of the nonreserved values listed in Table 69.

Table 69—Valid disassociation reason codes

Disassociate reason	**Description**
0x00	Reserved.
0x01	The coordinator wishes the device to leave the WPAN.
0x02	The device wishes to leave the WPAN.
0x03–0x7f	Reserved.
0x80–0xff	Reserved for MAC primitive enumeration values.

7.4.4 Data request command

The data request command is sent by a device to request data from the coordinator or a coordinator.

There are three cases for which this command is sent. On a beacon-enabled WPAN, this command shall be sent by a device when *macAutoRequest* is equal to TRUE and a beacon frame indicating that data are pending for that device is received from its coordinator. The coordinator indicates pending data in its beacon frame by adding the address of the recipient of the data to the Address List field. This command shall also be sent when instructed to do so by the next higher layer on reception of the MLME-POLL.request primitive. In addition, a device may send this command to the coordinator *macResponseWaitTime* symbols after the acknowledgment to an association request command.

All devices shall be capable of transmitting this command, although an RFD is not required to be capable of receiving it.

The data request command shall be formatted as illustrated in Figure 71.

octets: (see 7.2.2.6)	1
MHR fields	Command Frame Identifier (see Table 66)

Figure 71—Data request command format

If the data request command is being sent in response to the receipt of a beacon frame indicating that data are pending for that device, the Destination Addressing Mode subfield of the Frame Control field may be set to zero (i.e., destination addressing information not present) if the beacon frame indicated in its Superframe Specification field (see 7.2.2.1.2) that it originated from the coordinator (see 7.2.1.1.6) or set otherwise according to the coordinator to which the data request command is directed. If the destination addressing information is to be included, the Destination Addressing Mode subfield shall be set according to the value of *macCoordShortAddress*. If *macCoordShortAddress* is equal to 0xfffe, extended addressing shall be used: the Destination Addressing Mode subfield shall be set to three, and the Destination Address field shall contain the value of *macCoordExtendedAddress*. Otherwise, short addressing shall be used: the Destination Addressing Mode subfield shall be set to two, and the Destination Address field shall contain the value of *macCoordShortAddress*.

If the data request command is being sent in response to the receipt of a beacon frame indicating that data are pending for that device, the Source Addressing Mode subfield shall be set according to the addressing mode used for the pending address. If the Source Addressing Mode subfield is set to two, short addressing shall be used: the Source Address field shall contain the value of *macShortAddress*. Otherwise, extended addressing shall be used: the Source Addressing Mode subfield shall be set to three, and the Source Address field shall contain the value of *aExtendedAddress*.

If the data request command is triggered by the reception of an MLME-POLL.request primitive from the next higher layer, then the destination addressing information shall be the same as that contained in the primitive. The Source Addressing Mode subfield shall be set according to the value of *macShortAddress*. If *macShortAddress* is less than 0xfffe, short addressing shall be used. Extended addressing shall be used otherwise.

If the data request command is being sent following the acknowledgment to an association request command frame, the Destination Addressing Mode subfield of the Frame Control field shall be set according to the coordinator to which the data request command is directed. If *macCoordShortAddress* is equal to 0xfffe, extended addressing shall be used. Short addressing shall be used otherwise. The Source Addressing Mode subfield shall be set to use extended addressing.

If the Destination Addressing Mode subfield is set to zero (i.e., destination addressing information not present), the WPAN ID Compression subfield of the Frame Control field shall be set to zero and the source WPAN identifier shall contain the value of *macWPANId*. Otherwise, the WPAN ID Compression subfield shall be set to one. In this case and in accordance with the WPAN ID Compression subfield, the Destination WPAN Identifier field shall contain the value of *macWPANId*, while the Source WPAN Identifier field shall be omitted.

The Frame Pending subfield of the Frame Control field shall be set to zero and ignored upon reception, and the Acknowledgment Request subfield shall be set to one.

7.4.5 WPAN ID conflict notification command

The WPAN ID conflict notification command is sent by a device to the coordinator when a WPAN identifier conflict is detected.

All devices shall be capable of transmitting this command, although an RFD is not required to be capable of receiving it.

The WPAN ID conflict notification command shall be formatted as illustrated in Figure 72.

octets: (see 7.2.2.6)	1
MHR fields	Command Frame Identifier (see Table 66)

Figure 72—WPAN ID conflict notification command format

The Destination Addressing Mode and Source Addressing Mode subfields of the Frame Control field shall both be set to three (i.e., 64-bit extended addressing).

The Frame Pending subfield of the Frame Control field shall be set to zero and ignored upon reception, and the Acknowledgment Request subfield shall be set to one.

The WPAN ID Compression subfield of the Frame Control field shall be set to one. In accordance with this value of the WPAN ID Compression subfield, the Destination WPAN Identifier field shall contain the value of *macWPANId*, while the Source WPAN Identifier field shall be omitted. The Destination Address field shall contain the value of *macCoordExtendedAddress*. The Source Address field shall contain the value of *aExtendedAddress*.

7.4.6 Orphan notification command

The orphan notification command is used by an associated device that has lost synchronization with its coordinator.

All devices shall be capable of transmitting this command, although an RFD is not required to be capable of receiving it.

The orphan notification command shall be formatted as illustrated in Figure 73.

octets: 15	1
MHR fields	Command Frame Identifier (see Table 66)

Figure 73—Orphan notification command format

The Source Addressing Mode subfield of the Frame Control field shall be set to three (i.e., 64-bit extended addressing). The Destination Addressing Mode subfield shall be set to two (i.e., 16-bit short addressing).

The Frame Pending subfield and Acknowledgment Request subfield of the Frame Control field shall be set to zero and ignored upon reception.

The WPAN ID Compression subfield of the Frame Control field shall be set to one. In accordance with this value of the WPAN ID Compression subfield, the Destination WPAN Identifier field shall contain the value of the broadcast WPAN identifier (i.e., 0xffff), while the Source WPAN Identifier field shall be omitted. The Destination Address field shall contain the broadcast short address (i.e., 0xffff). The Source Address field shall contain the value of *aExtendedAddress*.

7.4.7 Beacon request command

The beacon request command is used by a device to locate all coordinators within its POS during an active scan.

This command is optional for an RFD.

The beacon request command shall be formatted as illustrated in Figure 74.

octets: 7	**1**
MHR fields	Command Frame Identifier (see Table 66)

Figure 74—Beacon request command format

The Destination Addressing Mode subfield of the Frame Control field shall be set to two (i.e., 16-bit short addressing), and the Source Addressing Mode subfield shall be set to zero (i.e., source addressing information not present).

The Frame Pending subfield of the Frame Control field shall be set to zero and ignored upon reception. The Acknowledgment Request subfield and Security Enabled subfield shall also be set to zero.

The Destination WPAN Identifier field shall contain the broadcast WPAN identifier (i.e., 0xffff). The Destination Address field shall contain the broadcast short address (i.e., 0xffff).

7.4.8 Coordinator realignment command

The coordinator realignment command is sent by the coordinator or a coordinator either following the reception of an orphan notification command from a device that is recognized to be on its WPAN or when any of its WPAN configuration attributes change due to the receipt of an MLME-START.request primitive.

If this command is sent following the reception of an orphan notification command, it is sent directly to the orphaned device. If this command is sent when any WPAN configuration attributes (i.e., WPAN identifier, short address, logical channel, or channel page) change, it is broadcast to the WPAN.

All devices shall be capable of receiving this command, although an RFD is not required to be capable of transmitting it.

The coordinator realignment command shall be formatted as illustrated in Figure 75.

octets: 17/18/23/24	1	2	2	1	2	0/1
MHR fields	Command Frame Identifier (see Table 66)	WPAN Identifier	Coordinator Short Address	Logical Channel	Short Address	Channel page

Figure 75—Coordinator realignment command format

7.4.8.1 MHR fields

The Destination Addressing Mode subfield of the Frame Control field shall be set to three (e.g., 64-bit extended addressing) if the command is directed to an orphaned device or set to two (e.g., 16-bit short addressing) if it is to be broadcast to the VLC WPAN. The Source Addressing Mode subfield of the Frame Control field shall be set to three (e.g., 64-bit extended addressing).

The Frame Pending subfield of the Frame Control field shall be set to zero and ignored upon reception.

The Acknowledgment Request subfield of the Frame Control field shall be set to one if the command is directed to an orphaned device or set to zero if the command is to be broadcast to the VLC WPAN.

The Frame Version subfield shall be set to 0x01 if the Channel Page field is present. Otherwise it shall be set as specified in 7.2.3.

The Destination WPAN Identifier field shall contain the broadcast WPAN identifier (e.g., 0xffff). The Destination Address field shall contain the extended address of the orphaned device if the command is directed to an orphaned device. Otherwise, the Destination Address field shall contain the broadcast short address (e.g., 0xffff). The Source WPAN Identifier field shall contain the value of *macWPANId*, and the Source Address field shall contain the value of *aExtendedAddress*.

7.4.8.2 WPAN Identifier field

The WPAN Identifier field shall contain the WPAN identifier that the coordinator intends to use for all future communications.

7.4.8.3 Coordinator Short Address field

The Coordinator Short Address field shall contain the value of *macShortAddress*.

7.4.8.4 Logical Channel field

The Logical Channel field shall contain the logical channel that the coordinator intends to use for all future communications.

7.4.8.5 Short Address field

If the coordinator realignment command is broadcast to the VLC WPAN, the Short Address field shall be set to 0xffff and ignored on reception.

If the coordinator realignment command is sent directly to an orphaned device, this field shall contain the short address that the orphaned device shall use to operate on the VLC WPAN. If the orphaned device does not have a short address, because it always uses its 64-bit extended address, this field shall contain the value 0xfffe.

7.4.8.6 Channel Page field

The Channel Page field, if present, shall contain the channel page that the coordinator intends to use for all future communications. This field may be omitted if the new channel page is the same as the previous channel page.

7.4.9 GTS request command

The GTS request command is used by an associated device that is requesting the allocation of a new GTS or the deallocation of an existing GTS from the coordinator. Only devices that have a 16-bit short address less than 0xfffe shall send this command.

This command is optional.

The GTS request command shall be formatted as illustrated in Figure 78.

octets: 7	1	1	2
MHR fields	Command Frame Identifier (see Table 66)	GTS Characteristics	Codeword IE

Figure 76—GTS request command format

7.4.9.1 MHR fields

The Destination Addressing Mode subfield of the Frame Control field shall be set to zero (e.g., destination addressing information not present), and the Source Addressing Mode subfield shall be set to two (e.g., 16-bit short addressing).

The Frame Pending subfield of the Frame Control field shall be set to zero and ignored upon reception, and the Acknowledgment Request subfield shall be set to one.

The Source WPAN Identifier field shall contain the value of *macWPANId*, and the Source Address field shall contain the value of *macShortAddress*.

7.4.9.2 GTS Characteristics field

The GTS Characteristics field shall be formatted as illustrated in Figure 79.

bits: 0–3	4	5	6–7
GTS Length	GTS Direction	Characteristics Type	Reserved

Figure 77—GTS Characteristics field format

The GTS Length subfield shall contain the number of superframe slots being requested for the GTS.

The GTS Direction subfield shall be set to one if the GTS is to be a receive-only GTS. Conversely, this subfield shall be set to zero if the GTS is to be a transmit-only GTS. GTS direction is defined relative to the direction of data frame transmissions by the device.

The Characteristics Type subfield shall be set to one if the characteristics refers to a GTS allocation or zero if the characteristics refers to a GTS deallocation.

7.4.10 Blinking notification command

octets: 7	1	1	2
MHR fields	Command Frame Identifier	Blinking frequency	Blinking color (band plan)

Depending on the FOV, TX power and the mobility of devices, it is possible that the link may occur only in 1 direction. In such cases, the mobile needs to change the visibility indication from continuous visibility for point-and-shoot to blinking indication. For example, if the infrastructure cannot receive uplink but the mobile is able to receive downlink, the AP can indicate to mobile about the lack of reception and request a visibility indicator change for the user. The mobile can then change from point-and-shoot mode to blinking mode to indicate the user that the connection may be getting disconnected. This indication can be applied to both P2MP and P2P modes of operation

7.4.11 Dimming notification command

octets: 7	1	2	2
MHR fields	Command Frame Identifier	Dimming level	Dimming link adaptation timer

(Table 1) Dimming notification command format

The dimming level is two bytes long and contains a value between 0 and 1000, where 0 represents 0% visibility and 1000 represents 100% visibility. The dimming levels are defined with a resolution of 0.1%. The dimming link adaptation timer provides a resolution of 0-16383 MAC clock cycles.

7.4.12 Mobility notification command

octets: 7	1	xx
MHR fields	Command Frame Identifier	Mobility fields

(Table 1) Mobility notification command

Management payload field	bit	usage
Src_multi_info	5 bit	Source multi channel information
Des_multi_info	5 bit	Destination multi channel information
H_pattern	5 bit	Hopping pattern
VF_info	2 bit	Visible frame information
Src_mode	3 bit	Source mode
G_cell_ID	10 bit	Definition of cell size
Fractional_Src	2 bit	1: yes (fractional cell configuration) 0 : no (general cell configuration)
Mode_type	2 bit	Mode type
S_Release_slot	5 bit	Slot release
MS_ID	10 bit	Mobile Station ID
# of time slot	5 bit	Number of time slot
Cell_info	10 bit	Cell ID and optical source ID (ex Cell n_ID_n)
B_info	2 bit	Cell boundary alarm information
S_info	5 bit	virtual time slot assignment information

7.4.12.1 Codeword IE

For this Codeword IE, one of 64 orthogonal sixteen bit codewords is assigned. These sixteen bit codewords can be generated by the same procedure as in 7.3.1.

Any device who wants to request a GTS slot selects one of 64 combinations of codewords randomly and sends it in the Codeword IE field of the GTS Request command. If the coordinator receives this request and decides to allocate a GTS slot to this device, it will send the same codeword that it received from that device

Table 70—Management payload

Management payload field	bit	usage
Src_multi_info	5	source multiple channel resource assignment 00000 : No multiple channel application
Des_multi_info	5	destination multiple channel resource assignment
H_pattern	5	multiple channel hopping when Src_multi_info is 00000, then no H_pattern application
VF_info_type	1	Visible Frame transmission 1: Receiver VF transmission 0: Non receiver VF transmission (do not use VF in receiver)
G_cell_ID	10	granular cell assignment
Source_ID	10	Current optical source ID
Fractional_Src	2	frame source notifications
Mode_type	2	multicast, broadcast, unicast
S_release_slot	5	start and release slot for broadcast
spatial mobility	4	request spatial mobility
MS_ID	10	terminal ID or user ID
# of time slot	5	number of time slot
Cell_info	10	Cell ID (PD_ID) or AP ID
B_info	2	cell boundary information
S_info	5	virtual time slot assignment

to notify that a GTS slot is allocated to the device. If more than one device send request of association simultaneously, the coordinator selects one of them and sends exactly the same codeword among 64 combinations that was sent by the selected device in the Codeword IE of the GTS Response command to notify that this device is allowed to send a frame in the allocated GTS slot. If more than one device selects the same codeword among 64 combinations with different source address, collision occurs and random back-off algorithm is applied by resending request commands with random back-offs.

7.4.13 GTS response command

The GTS.response primitive is used generated in response to a GTS.requirest primitve.

This command is optional.

The GTS response command shall be formatted as illustrated in Figure 51.

7.4.13.1 MHR fields

The Destination Addressing Mode subfield of the Frame Control field shall be set to zero (e.g., destination addressing information not present), and the Source Addressing Mode subfield shall be set to two (e.g., 16-bit short addressing).

octets: 7	1	1	1	2
MHR fields	Command Frame Identifier (see Table 66)	GTS Characteristics	GTS Starting Slot	Codeword IE

Figure 78—GTS response command format

The Frame Pending subfield of the Frame Control field shall be set to zero and ignored upon reception, and the Acknowledgment Request subfield shall be set to one.

The Source WPAN Identifier field shall contain the value of *macWPANId*, and the Source Address field shall contain the value of *macShortAddress*.

7.4.13.2 GTS Characteristics field

The GTS Characteristics field shall be formatted as illustrated in Figure 79.

bits: 0–3	4	5	6–7
GTS Length	GTS Direction	Characteristics Type	Reserved

Figure 79—GTS Characteristics field format

The GTS Length subfield shall contain the number of superframe slots being requested for the GTS.

The GTS Direction subfield shall be set to one if the GTS is to be a receive-only GTS. Conversely, this subfield shall be set to zero if the GTS is to be a transmit-only GTS. GTS direction is defined relative to the direction of data frame transmissions by the device.

The Characteristics Type subfield shall be set to one if the characteristics refers to a GTS allocation or zero if the characteristics refers to a GTS deallocation.

7.4.13.3 GTS Starting Slot

TBD

7.4.13.4 Codeword IE

For this Codeword IE, one of 64 orthogonal sixteen bit codewords is assigned. These sixteen bit codewords can be generated by the same procedure as in 7.3.1. Operational procedure is also described in 7.4.9.3.

7.5 MAC constants and PIB attributes

This subclause specifies the constants and attributes required by the MAC sublayer.

7.5.1 MAC constants

The constants that define the characteristics of the MAC sublayer are presented in Table 71.

Table 71—MAC sublayer constants

Constant	Description	Value
aBaseSlotDuration	The number of symbols forming a superframe slot when the superframe order is equal to 0 (see 7.7.1.1).	60
aBaseSuperframeDuration	The number of symbols forming a superframe when the superframe order is equal to 0.	*aBaseSlotDuration* * *aNumSuperframeSlots*
aExtendedAddress	The 64-bit (IEEE) address assigned to the device.	Device specific
aGTSDescPersistenceTime	The number of superframes in which a GTS descriptor exists in the beacon frame of the coordinator.	4
aMaxBeaconOverhead	The maximum number of octets added by the MAC sublayer to the MAC payload of a beacon frame.	75
aMaxBeaconPayloadLength	The maximum size, in octets, of a beacon payload.	*aMaxPHYPacketSize* – *aMaxBeaconOverhead*
aMaxLostBeacons	The number of consecutive lost beacons that will cause the MAC sublayer of a receiving device to declare a loss of synchronization.	4
aMaxMACSafePayloadSize	The maximum number of octets that can be transmitted in the MAC Payload field of an unsecured MAC frame that will be guaranteed not to exceed *aMaxPHYPacketSize*.	*aMaxPHYPacketSize* – *aMaxMPDUUnsecuredOverhead*
aMaxMACPayloadSize	The maximum number of octets that can be transmitted in the MAC Payload field.	*aMaxPHYPacketSize* – *aMinMPDUOverhead*
aMaxMPDUUnsecuredOverhead	The maximum number of octets added by the MAC sublayer to the PSDU without security.	25
aMaxSIFSFrameSize	The maximum size of an MPDU, in octets, that can be followed by a SIFS period.	18
aMinCAPLength	The minimum number of symbols forming the CAP. This ensures that MAC commands can still be transferred to devices when GTSs are being used. An exception to this minimum shall be allowed for the accommodation of the temporary increase in the beacon frame length needed to perform GTS maintenance (see 7.2.2.1.3).	440
aMinMPDUOverhead	The minimum number of octets added by the MAC sublayer to the PSDU.	9
aNumSuperframeSlots	The number of slots contained in any superframe.	16
aUnitBackoffPeriod	The number of symbols forming the basic time period used by the random access algorithm.	20

7.5.2 MAC PIB attributes

The MAC PIB comprises the attributes required to manage the MAC sublayer of a device. The attributes contained in the MAC PIB are presented in Table 31. Attributes marked with a dagger (†) are read-only attributes (i.e., attribute can only be set by the MAC sublayer), which can be read by the next higher layer using the MLME-GET.request primitive. All other attributes can be read or written by the next higher layer using the MLME-GET.request or MLME-SET.request primitives, respectively. Attributes marked with a diamond (◆) are optional for an RFD; attributes marked with an asterisk (*) are optional for both device types (i.e., RFD and FFD).

The read-only attribute *macAckWaitDuration* is dependent on a combination of constants and PHY PIB attributes. The formula for relating the constants and attributes is shown in Equation (2).

$$macAckWaitDuration = \quad (2)$$

$$aUnitBackoffPeriod + aTurnaroundTime + phySHRDuration + \lceil 6 \cdot phySymbolsPerOctet \rceil$$

where
6 represents the number of PHY header octets plus the number of PSDU octets in an acknowledgment frame.

The attribute *macMaxFrameTotalWaitTime* may be set by the next higher layer and is dependent upon a combination of PHY and MAC PIB attributes and constants. The formula relating the attributes and constants is shown in Equation (3):

$$macMaxFrameTotalWaitTime = \quad (3)$$

$$\left[\left(\sum_{k=0}^{m-1} 2^{macMinBE + k}\right) + (2^{macMaxBE} - 1) \cdot (macMaxCSMABackoffs - m)\right] \bullet aUnitBackoffPeriod + phyMaxFrameDuration$$

where
m is min(*macMaxBE-macMinBE, macMaxCSMABackoffs).*

For the mandatory data rate (1 Mb/s), *macAckWaitDuration* is calculated as shown in Equation (4).

$$macAckWaitDuration_{1M} = aUnitBackoffPeriod + aTurnaroundTime + phySHRDuration_{1M} + [1.5 + 3/4 \times ceiling(4/3 \times 5)] \times phySymbolsPerOctet_{1M} \quad (4)$$

For the optional data rate (250 kb/s), *macAckWaitDuration* is calculated as shown in Equation (5).

$$macAckWaitDuration_{250k} = aUnitBackoffPeriod + aTurnaroundTime + phySHRDuration_{250k} + 3 \times ceiling(1/3 \times [1.5 + 5]) \times phySymbolsPerOctet_{250k} \quad (5)$$

7.6 Visibility frame

Octets: 2	2	variable
Frame Control	Visibility level	Visibility pattern

The visibility level is two bytes long and contains a value between 0 and 1000, where 0 represents 0% visibility and 1000 represents 100% visibility. 1001- 1023 are reserved values. The visibility levels are defined with a resolution of 0.1%. There is no FCS required for the visibility frame. The visibility pattern sent shall have the same resolution that is mentioned in the visibility level. If there is a dimmer, the

Table 72—MAC PIB attributes

Attribute	Identifier	Type	Range	Description	Default
macAckWaitDuration†	0x40	Integer	See Equation (2), Equation (4), Equation (4), and Equation (5) for range as a function of PHY type	The maximum number of symbols to wait for an acknowledgment frame to arrive following a transmitted data frame. This value is dependent on the supported PHY, which determines both the selected logical channel and channel page. The calculated value is the time to commence transmitting the ACK plus the length of the ACK frame. The commencement time is described in 9.7.7.4.2.	Dependent on currently selected PHY, indicated by *phyCurrentPage*.
macAssociatedWPAN-Coord	0x56	Boolean	TRUE or FALSE	Indication of whether the device is associated to the WPAN through the coordinator. A value of TRUE indicates the device has associated through the coordinator. Otherwise, the value is set to FALSE.	FALSE
macAssociation-Permit◆	0x41	Boolean	TRUE or FALSE	Indication of whether a coordinator is currently allowing association. A value of TRUE indicates that association is permitted.	FALSE
macAutoRequest	0x42	Boolean	TRUE or FALSE	Indication of whether a device automatically sends a data request command if its address is listed in the beacon frame. A value of TRUE indicates that the data request command is automatically sent. This attribute also affects the generation of the MLME-BEACON-NOTIFY.indication primitive (see 7.1.5.1.2).	TRUE
macBattLifeExt	0x43	Boolean	TRUE or FALSE	Indication of whether BLE, through the reduction of coordinator receiver operation time during the CAP, is enabled. A value of TRUE indicates that it is enabled. Also, see 7.7.3.3 for an explanation of how this attribute affects the backoff exponent in the random access algorithm.	FALSE

Table 72—MAC PIB attributes *(continued)*

Attribute	Identifier	Type	Range	Description	Default
macBattLifeExtPeriods	0x44	Integer	6-41	In BLE mode, the number of backoff periods during which the receiver is enabled after the IFS following a beacon. This value is dependent on the supported PHY and is the sum of three terms: Term 1: The value $2^x - 1$, where *x* is the maximum value of *macMinBE* in BLE mode (equal to two). This term is thus equal to 3 backoff periods. Term 2: The duration of the initial contention window length (see 7.7.3.3). This term is thus equal to 2 backoff periods. Term 3: The Preamble field length and the SFD field length of the supported PHY (see Table 26 and Table 27 in Clause 6), summed together and rounded up (if necessary) to an integer number of back-off periods.	Dependent on currently selected PHY, indicated by *phy-Current-Page*
macBeaconPayload◆	0x45	Set of octets	—	The contents of the beacon payload.	NULL
macBeaconPayload-Length◆	0x46	Integer	0 – *aMax-Beacon-PayloadLength*	The length, in octets, of the beacon payload.	0
macBeaconOrder◆	0x47	Integer	0–15	Specification of how often the coordinator transmits its beacon. If *BO* = 15, the coordinator will not transmit a periodic beacon. See 7.7.1.1 for an explanation of the relationship between the beacon order and the beacon interval.	15

Table 72—MAC PIB attributes *(continued)*

Attribute	Identifier	Type	Range	Description	Default
macBeaconTxTime†◆	0x48	Integer	0x000000–0xffffff	The time that the device transmitted its last beacon frame, in symbol periods. The measurement shall be taken at the same symbol boundary within every transmitted beacon frame, the location of which is implementation specific. This is a 24-bit value, and the precision of this value shall be a minimum of 20 bits, with the lowest four bits being the least significant.	0x000000
macBSN◆	0x49	Integer	0x00–0xff	The sequence number added to the transmitted beacon frame.	Random value from within the range
macCoordExtended-Address	0x4a	IEEE address	An extended 64-bit IEEE address	The 64-bit address of the coordinator through which the device is associated.	—
macCoordShort-Address	0x4b	Integer	0x0000–0xffff	The 16-bit short address assigned to the coordinator through which the device is associated. A value of 0xfffe indicates that the coordinator is only using its 64-bit extended address. A value of 0xffff indicates that this value is unknown.	0xffff
macDSN	0x4c	Integer	0x00–0xff	The sequence number added to the transmitted data or MAC command frame.	Random value from within the range
*macGTSPermit**	0x4d	Boolean	TRUE or FALSE	TRUE if the coordinator is to accept GTS requests. FALSE otherwise.	TRUE
macMaxBE	0x57	Integer	3–15	The maximum value of the backoff exponent, BE, in the random access algorithm. See 7.7.3.3 for a detailed explanation of the backoff exponent.	5
macMaxCSMABackoffs	0x4e	Integer	0–5	The maximum number of backoffs the random access algorithm will attempt before declaring a channel access failure.	4

Table 72—MAC PIB attributes *(continued)*

Attribute	Identifier	Type	Range	Description	Default
macMaxFrameTotal-WaitTime	0x58	Integer	See Equation (3) and Equation (5)	The maximum number of CAP symbols in a beacon-enabled WPAN, or symbols in a nonbeacon-enabled WPAN, to wait either for a frame intended as a response to a data request frame or for a broadcast frame following a beacon with the Frame Pending subfield set to one. This attribute, which shall only be set by the next higher layer, is dependent upon *macMinBE*, *macMaxBE*, *macMaxCSMABackoffs* and the number of symbols per octet. See 7.5.2 for the formula relating the attributes.	Dependent on currently selected PHY, indicated by *phy-Current-Page*
macMaxFrameRetries	0x59	Integer	0–7	The maximum number of retries allowed after a transmission failure.	3
macMinBE	0x4f	Integer	0–*macMaxBE*	The minimum value of the backoff exponent (BE) in the random access algorithm. See 7.7.3.3 for a detailed explanation of the backoff exponent.	3
macMinLIFSPeriod†		Integer	See Table 5 in Clause 6	The minimum number of symbols forming a LIFS period.	Dependent on currently selected PHY, indicated by *phy-Current-Page*
macMinSIFSPeriod†		Integer	See Table 5 in Clause 6	The minimum number of symbols forming a SIFS period.	Dependent on currently selected PHY, indicated by *phy-Current-Page*
macWPANId	0x50	Integer	0x0000–0xffff	The 16-bit identifier of the WPAN on which the device is operating. If this value is 0xffff, the device is not associated.	0xffff

Table 72—MAC PIB attributes *(continued)*

Attribute	Identifier	Type	Range	Description	Default
macPromiscuous-Mode◆	0x51	Boolean	TRUE or FALSE	Indication of whether the MAC sublayer is in a promiscuous (receive all) mode. A value of TRUE indicates that the MAC sublayer accepts all frames received from the PHY.	FALSE
macRanging-Supported †	0x60	Boolean	TRUE or FALSE	This indicates whether the MAC sublayer supports the optional ranging features*.	Dependent on supported PHY and MAC capability.
macResponseWaitTime	0x5a	Integer	2–64	The maximum time, in multiples of *aBaseSuperframeDuration*, a device shall wait for a response command frame to be available following a request command frame.	32
macRxOnWhenIdle	0x52	Boolean	TRUE or FALSE	Indication of whether the MAC sublayer is to enable its receiver during idle periods. For a beacon-enabled WPAN, this attribute is relevant only during the CAP of the incoming superframe. For a nonbeacon-enabled WPAN, this attribute is relevant at all times.	FALSE
macSecurityEnabled	0x5d	Boolean	TRUE or FALSE	Indication of whether the MAC sublayer has security enabled. A value of TRUE indicates that security is enabled, while a value of FALSE indicates that security is disabled.	FALSE
macShortAddress	0x53	Integer	0x0000–0xffff	The 16-bit address that the device uses to communicate in the WPAN. If the device is the coordinator, this value shall be chosen before a WPAN is started. Otherwise, the address is allocated by a coordinator during association. A value of 0xfffe indicates that the device has associated but has not been allocated an address. A value of 0xffff indicates that the device does not have a short address.	0xffff

Table 72—MAC PIB attributes *(continued)*

Attribute	Identifier	Type	Range	Description	Default
macSuperframe-Order†◆	0x54	Integer	0–15	The length of the active portion of the outgoing superframe, including the beacon frame. If superframe order, *SO*, = 15, the superframe will not be active following the beacon. See 7.7.1.1 for an explanation of the relationship between the superframe order and the superframe duration.	15
macSyncSymbolOffset†	0x5b	Integer	0x000–0x100 for the 2.4 GHz PHY 0x000–0x400 for the 868/915 MHz PHY	The offset, measured in symbols, between the symbol boundary at which the MLME captures the timestamp of each transmitted or received frame, and the onset of the first symbol past the SFD, namely, the first symbol of the Length field.	Imple-mentation specific
macTimestamp-Supported†	0x5c	Boolean	TRUE or FALSE	Indication of whether the MAC sublayer supports the optional timestamping feature for incoming and outgoing data frames.	Imple-mentation specific
macTransaction-PersistenceTime◆	0x55	Integer	0x0000–0xffff	The maximum time (in unit periods) that a transaction is stored by a coordinator and indicated in its beacon. The unit period is governed by *macBeaconOrder*, *BO*, as follows: For $0 \leq BO \leq 14$, the unit period will be *aBase-SuperframeDuration* * 2^{BO}. For *BO = 15*, the unit period will be *aBaseSuperframe-Duration*.	0x01f4
macTxControlActiveDuration	0x61	Integer	0–100000	The duration for which transmit is permitted without pause specified in symbols.	TDB
macTxControlPauseDuration	0x62	Integer	2000 or 10000	The duration after transmission before another transmission is permitted specified in symbols.	TBD
macTxTotalDuration	0x63	Integer	0x0–0xffffffff	The total transmit duration (including PHY header and FCS) specified in symbols. This can be read and cleared by NHL.	0

dimming level shall be indicated as the visibility level. The visibility pattern will be generated by the PHY based on the visibility level setting. The visibility frame is used by infrastructure to maintain visibility at all times and by the mobile device for point-and-shoot.

7.7 MAC functional description

This subclause provides a detailed description of the MAC functionality. Subclause 7.7.1 describes the following two mechanisms for channel access: contention based and contention free. Contention-based access allows devices to access the channel in a distributed fashion using a random access backoff algorithm. Contention-free access is controlled entirely by the coordinator through the use of GTSs.

The mechanisms used for starting and maintaining a VLC WPAN are described in 9.7. Channel scanning is used by a device to assess the current state of a channel (or channels), locate all beacons within its POS, or locate a particular beacon with which it has lost synchronization. Before starting a new VLC WPAN, the results of a channel scan can be used to select an appropriate logical channel and channel page, as well as a WPAN identifier that is not being used by any other WPAN in the area. Because it is still possible for the POS of two WPANs with the same WPAN identifier to overlap, a procedure exists to detect and resolve this situation. Following a channel scan and suitable WPAN identifier selection, an FFD can begin operating as the coordinator. Also described in the subclause is a method to allow a beaconing FFD to discover other such devices during normal operations, i.e., when not scanning.

The mechanisms to allow devices to join or leave a WPAN are defined in 9.7.4. The association procedure describes the conditions under which a device may join a WPAN and the conditions necessary for a coordinator to permit devices to join. Also described is the disassociation procedure, which can be initiated by the associated device or its coordinator.

The mechanisms to allow devices to acquire and maintain synchronization with a coordinator are described in 9.7.5. Synchronization on a beacon-enabled VLC WPAN is described after first explaining how a coordinator generates beacon frames. Following this explanation, synchronization on a nonbeacon-enabled VLC WPAN is described. Also described is a procedure to reestablish communication between a device and its coordinator, as it is possible that a device may lose synchronization in the case of either a beacon-enabled or a nonbeacon-enabled VLC WPAN.

This standard has been designed so that application data transfers can be controlled by the devices on a VLC WPAN rather than by the coordinator. The procedures the coordinator uses to handle multiple transactions while preserving this requirement are described in 9.7.6.

The mechanisms for transmitting, receiving, and acknowledging frames, including frames sent using indirect transmission, are described in 9.7.7. In addition, methods for retransmitting frames are also described.

The mechanisms for allocating and deallocating a GTS are described in 9.7.8. The deallocation process may result in the fragmentation of the GTS space, i.e., an unused slot or slots. The subclause describes a mechanism to resolve fragmentation.

The MAC sublayer uses the mechanisms described in 9.7.9 for all incoming and outgoing frames.

Throughout this subclause, the receipt of a frame is defined as the successful receipt of the frame by the PHY and the successful verification of the FCS by the MAC sublayer, as described in 7.2.1.9.

7.7.1 Channel access

This subclause describes the mechanisms for accessing the physical optical channel. The standard provides a single VLC MAC frame that can be configured for multiple modes. The frame is composed of a variable number of slots. A slot can be defined as the minimum time needed to communicate to send the smallest data to a device and is fixed.

7.7.1.1 Superframe structure

A coordinator on a VLC WPAN can optionally bound its channel time using a superframe structure. A superframe is bounded by the transmission of a beacon frame and can have an active portion and an inactive portion. The coordinator may enter a low-power (sleep) mode during the inactive portion.

The structure of this superframe is described by the values of *macBeaconOrder* and *macSuperframeOrder*. The MAC PIB attribute *macBeaconOrder*, describes the interval at which the coordinator shall transmit its beacon frames. The value of *macBeaconOrder*, *BO*, and the beacon interval, *BI*, are related as follows: for $0 \leq BO \leq 14$, $BI = aBaseSuperframeDuration * 2^{BO}$ symbols. If $BO = 15$, the coordinator shall not transmit beacon frames except when requested to do so, such as on receipt of a beacon request command. The value of *macSuperframeOrder* shall be ignored if $BO = 15$.

The MAC PIB attribute *macSuperframeOrder* describes the length of the active portion of the superframe, which includes the beacon frame. The value of *macSuperframeOrder*, *SO*, and the superframe duration, *SD*, are related as follows: for $0 \leq SO \leq BO \leq 14$, $SD = aBaseSuperframeDuration * 2^{SO}$ symbols. If $SO = 15$, the superframe shall not remain active after the beacon. If $BO = 15$, the superframe shall not exist (the value of *macSuperframeOrder* shall be ignored), and *macRxOnWhenIdle* shall define whether the receiver is enabled during periods of transceiver inactivity.

The active portion of each superframe shall be divided into *aNumSuperframeSlots* equally spaced slots of duration $2^{SO} * aBaseSlotDuration$ and is composed of three parts: a beacon, a CAP and a CFP. The beacon shall be transmitted, without the use of random access, at the start of slot 0, and the CAP shall commence immediately following the beacon. The start of slot 0 is defined as the point at which the first symbol of the beacon PPDU is transmitted. The CFP, if present, follows immediately after the CAP and extends to the end of the active portion of the superframe. Any allocated GTSs shall be located within the CFP.

The MAC sublayer shall ensure that the integrity of the superframe timing is maintained, e.g., compensating for clock drift error.

WPANs that wish to use the superframe structure (referred to as a beacon-enabled WPAN) shall set *macBeaconOrder* to a value between 0 and 14, both inclusive, and *macSuperframeOrder* to a value between 0 and the value of *macBeaconOrder*, both inclusive.

WPANs that do not wish to use the superframe structure (referred to as a nonbeacon-enabled WPAN) shall set both *macBeaconOrder* and *macSuperframeOrder* to 15. In this case, a coordinator shall not transmit beacons, except upon receipt of a beacon request command; all transmissions, with the exception of acknowledgment frames and any data frame that quickly follows the acknowledgment of a data request command (see 9.7.7.3), shall use an unslotted random access mechanism to access the channel. In addition, GTSs shall not be permitted.

(Informative) An example of a superframe structure is shown in Figure 80. In this case, the beacon interval, *BI*, is twice as long as the active superframe duration, *SD*, and the CFP contains two GTSs.

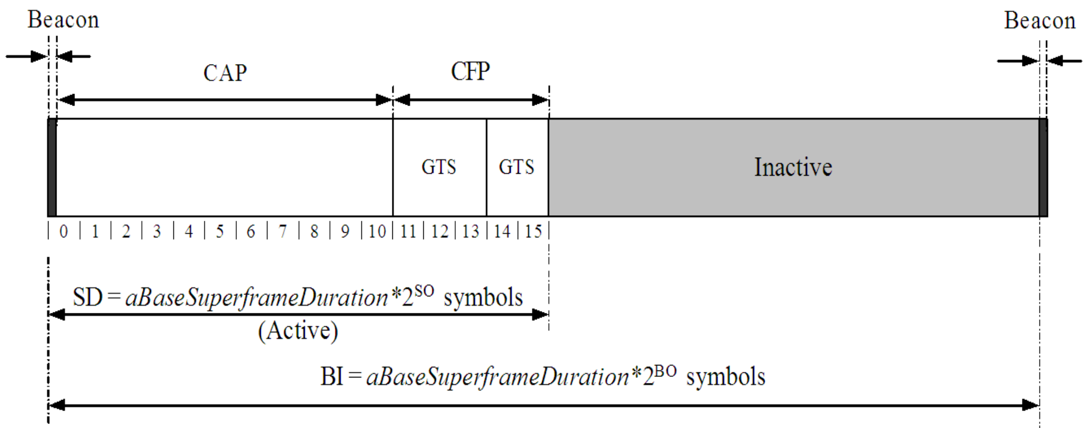


Figure 80—An example of the superframe structure

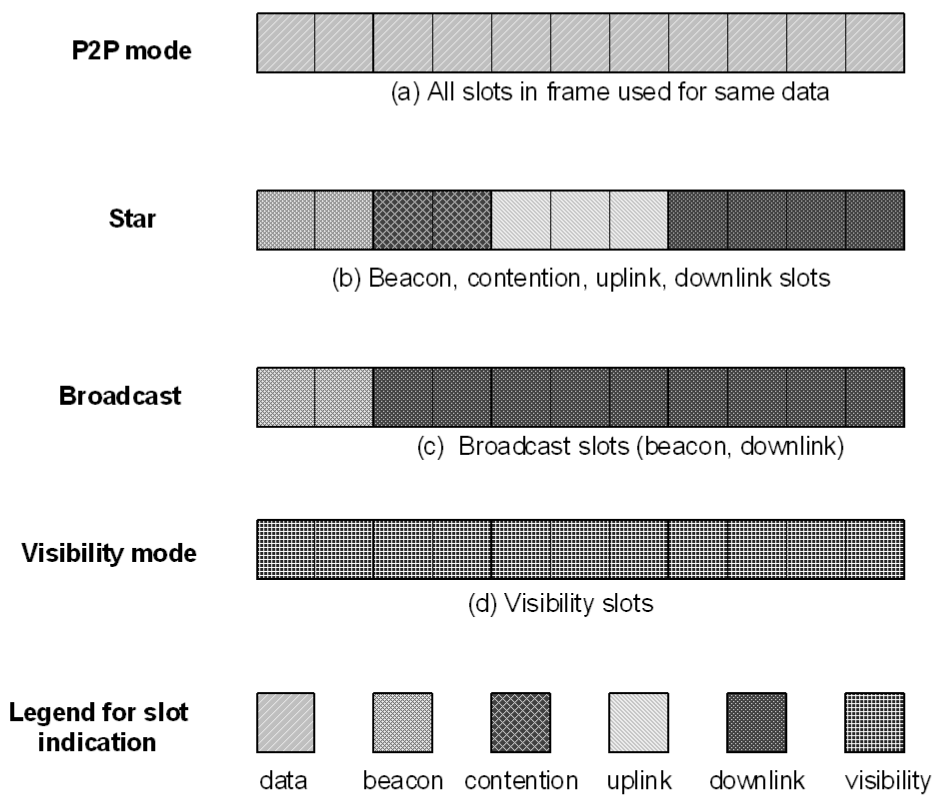


Figure 81—Example usage of frame structure for multiple topologies (informative)

The CAP and CPF slots are used in a flexible manner as shown in Figure 81. The contention slots are used in the CAP period. The uplink and downlink slots are used in the CFP periods. The visibility slots are used during idle or RX modes of the infrastructure to ensure continuous output and remove flicker and are also used for point-and-shoot mode to ensure visibility.

7.7.1.1.1 Contention access period (CAP)

The CAP shall start immediately following the beacon and complete before the beginning of the CFP on a superframe slot boundary. If the CFP is zero length, the CAP shall complete at the end of the active portion of the superframe. The CAP shall be at least *aMinCAPLength* symbols, unless additional space is needed to temporarily accommodate the increase in the beacon frame length needed to perform GTS maintenance (see 7.2.2.1.3), and shall shrink or grow dynamically to accommodate the size of the CFP.

All frames, except acknowledgment frames and any data frame that quickly follows the acknowledgment of a data request command (see 9.7.7.3), transmitted in the CAP shall use a slotted random access mechanism to access the channel. A device transmitting within the CAP shall ensure that its transaction is complete (i.e., including the reception of any acknowledgment) one IFS period (see 7.7.3.2) before the end of the CAP. If this is not possible, the device shall defer its transmission until the CAP of the following superframe.

MAC command frames shall always be transmitted in the CAP.

7.7.1.1.2 Contention-free period (CFP)

The CFP shall start on a slot boundary immediately following the CAP and it shall complete before the end of the active portion of the superframe. If any GTSs have been allocated by the coordinator, they shall be located within the CFP and occupy contiguous slots. The CFP shall therefore grow or shrink depending on the total length of all of the combined GTSs. Communication between devices can take a variable number of slots. A single device or user can have access to more than a single slot for sustained data transfer in the frame, if there are slots available.

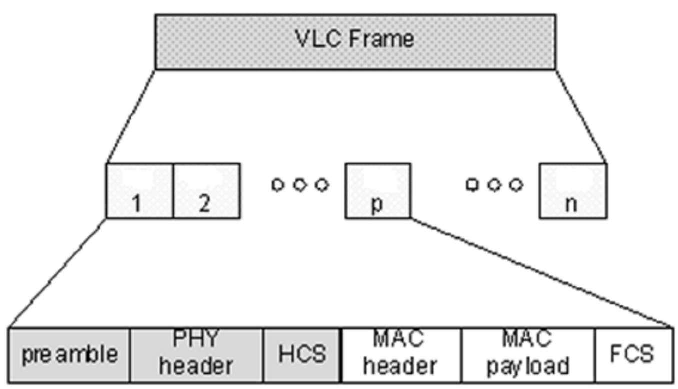


Figure 82—Example of slot usage by a particular VLC device

No transmissions within the CFP shall use a random access mechanism to access the channel. A device transmitting in the CFP shall ensure that its transmissions are complete one IFS period (see 7.7.3.2) before the end of its GTS.

7.7.1.1.3 Visibility support during channel access

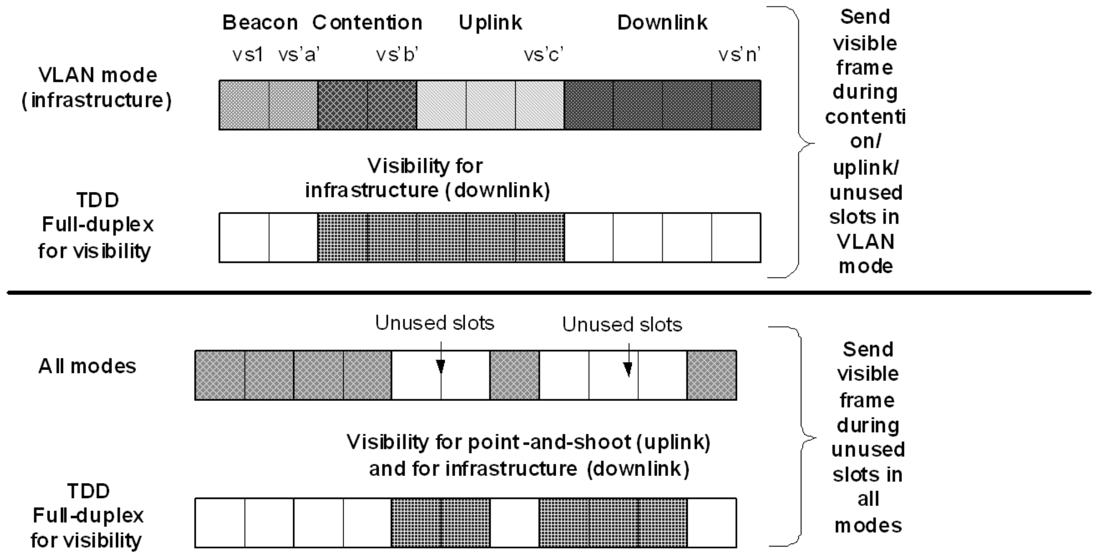


Figure 83—Usage of visible frames during idle or RX modes of operation

The visibility slots can be used during contention and uplink slots in star topology mode and unused slots in all modes to maintain visibility, reduce flicker and keep the transmitter always "ON" for the infrastructure. This is shown in Figure 83. This is a very important distinguishing feature of the VLC MAC frame format support for VLC. Thus, although TDD duplexing can be used and half-duplexing can be done for data communication, visibility patterns may need to be transmitted during receive and idle modes using full duplex operation to maintain and support visibility. The full duplexing in TDD mode is possible due to spatial separation of the light source and the receiving circuitry. As shown in Figure 57, visible patterns are sent during contention, uplink slots and unused downlink slots by the infrastructure to maintain visibility. Visible patterns are also sent during unused slots by the mobile device to help with pointing and alignment for optimal data transfer.

7.7.1.2 Data transmission modes

We provide multiple modes for transmitting data and control between the transmitter and receiver with reduced preamble repetition options for different VLC Modes. For example, three different modes such as single, packed and burst modes are provided that can service all VLC Modes. This is as shown in Figure xx. In the single mode, there is only one PDU transferred per frame. Hence, this is used for very short data communication such as acknowledgements or association or beaconing or for vehicular broadcasting modes. The packed mode contains multiple PDUs per frame and is used to send multiple consecutive PDUs to the same destination within the frame for high throughput. Thus, the overhead of sending multiple MAC and PHY headers to the same destination is eliminated in this mode, providing higher MAC efficiency. This can be used in most modes as the preferred means of data communication. It is also possible for P2P types of communication to send long streams of data to the same destination even across frames. In such cases, a burst mode can be used that can reduce the preamble repetitions and the interframe spacing (IFS) between the consecutive frames. The reduced number of preambles improves the throughput of the system and eliminates the inefficiency of retraining the whole receiver since the previous frame was also sent to the receiver from the same transmitter. The Short Interframe Spacing (SIFS) between frames can also be reduced to Reduced Interframe Spacing (RIFS) since the next frame is also from the same source for the same destination. We provide the ability to have flexible preamble repetitions in this mode, allowing the transmitter and receiver to optimize the preamble repetitions by using feedback and/or based on the capabilities of the devices and the Mode. The reduced number of preamble repetitions can be indicated in the PHY header for the next frame in the burst mode.

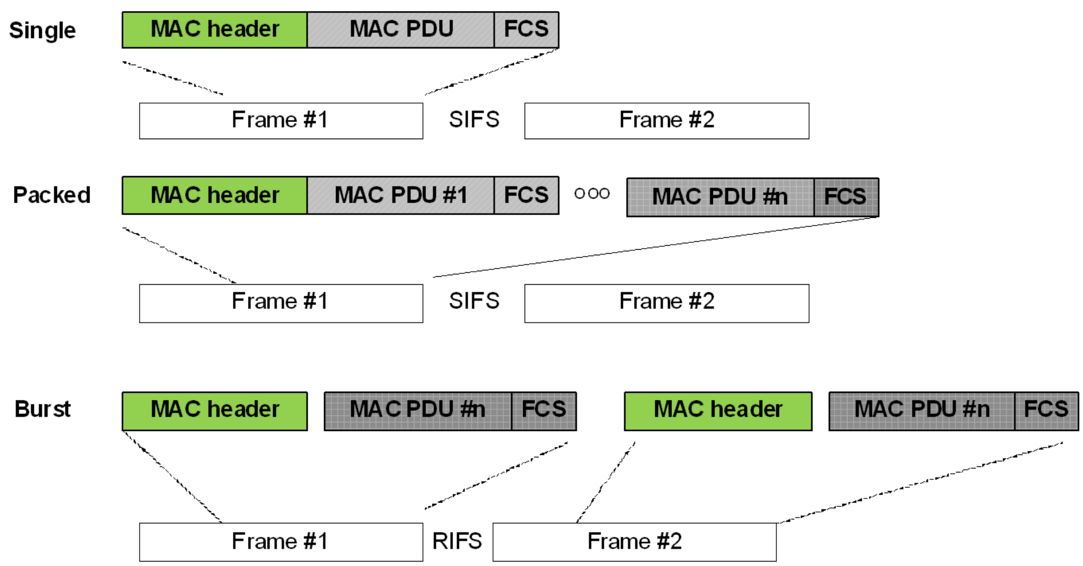


Figure 84—Different data types supported by the MAC (single, packed, burst)

An example of the data and control modes for different Modes is shown in Table 53. Acknowledgements and management frames use the single mode since they only transfer a limited amount of data. Even though acknowledgements may be desired for packed or burst modes, which may be involving sequence numbers across multiple frames, they can still be sent in the payload of the single mode.

(Table 1) Data and control modes for different VLC Modes

Mode	Type of communication	Data and control mode
P2P, VLAN	Management, Acknowledgement	Single
IB, VB, VLAN	Beacon	Single
P2P	Data	Burst, Packed
VLAN	Data	Single, Packed
IB	Data	Single, Packed
VB	Data	Single

7.7.2 Starting and maintaining PANs

This sub clause specifies the procedures for scanning through channels, identifying PAN identifier conflicts, and starting PANs.

7.7.2.1 Guard and aggregation color channels

The bandplan provides support for 7 logical channels in the MAC. However, in order to support association without knowledge of receiver capabilities and to support unidirectional broadcasting, the VLC receiver shall support reception on the entire visible light spectrum with any type of optical light source.

Channel aggregation is used to indicate optical sources that span multiple (>1) bands in the proposed bandplan and are intentionally transmitting on multiple bands due to the choice of optical light source. Guard channels are used to indicate optical sources that unintentionally leak into other bands, whose information can be discarded at the receiver for better performance.

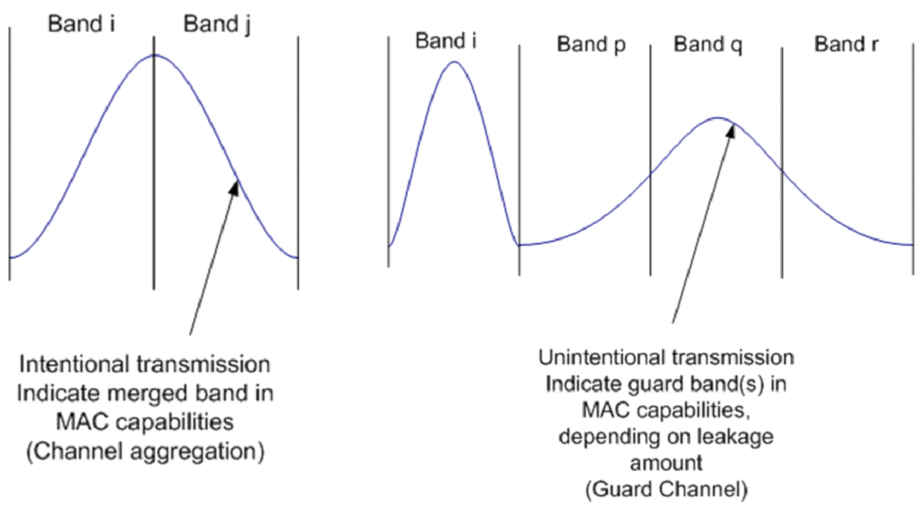


Figure 85—Concept of aggregation channel and guard channel

If multiple bands are aggregated or multiple optical sources are transmitting simultaneously, the same data shall be sent on all optical sources during the preamble and header during link establishment since it is not known what the receiver capabilities are. The details on channel aggregation and guard channel support are provided in the PHY capabilities information element of the MAC. The criterion used for defining a guard color channel or aggregated channel is based on out-of-band leakage, exceeding 20 dB over maximum in-channel value. The transmitting device shall indicate channel aggregation and guard channel support using the PHY capabilities during device discovery and association for bi-directional communication modes.

7.7.3 VLC TDM support for LED Signboard: Multiplexing (informative)

It consists with a host controller, line scan IC, Data IC and led matrix. Line scan IC selects a line for specific data stream and data IC transmit on/off or color selection information of each dot on the selected line. Line scan is active high, and data is active low. Line scan determines the operating time of each line. Operating time means LED On time duration of selected line.

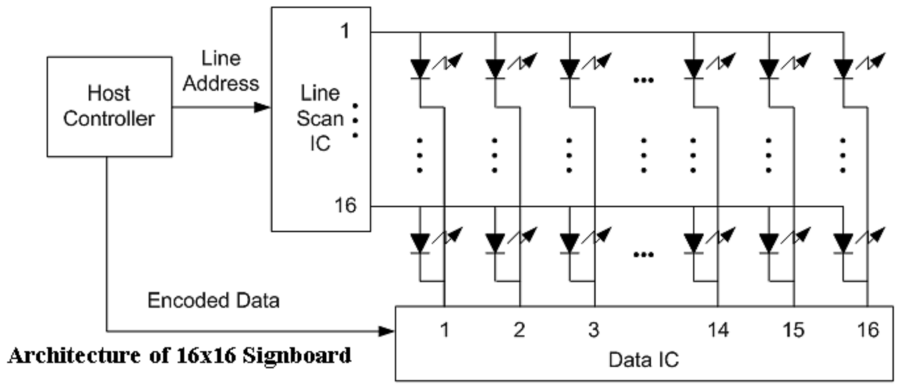


Figure 86—Architecture of general LED signboard

General PC monitor and TV transmit 60 frames per second. One frame is transmitted twice, it is same with transmission of 30 different frames per second. At LED signboard, frame transmission mechanism is similar to PC monitor and TV. 16 Lines have to operate 60 times during 1 second in case of 16 by 16 LED signboard. The operating time for 1 line is about 1ms: (1s/60f)/16fpl ? 1ms/l. At the signboard industry, generally 25 to 60 fps is used.

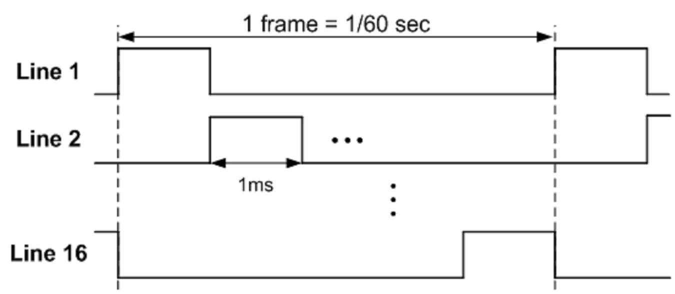


Figure 87—Operation of 16x16 Signboard

Line operating time 1ms is fixed at one signboard. So, we can arrange 1 ms for 1 time slot.

16 time slots are possible. For example, if we consider 1Mbps, 1 time slot can transmit 125bytes.

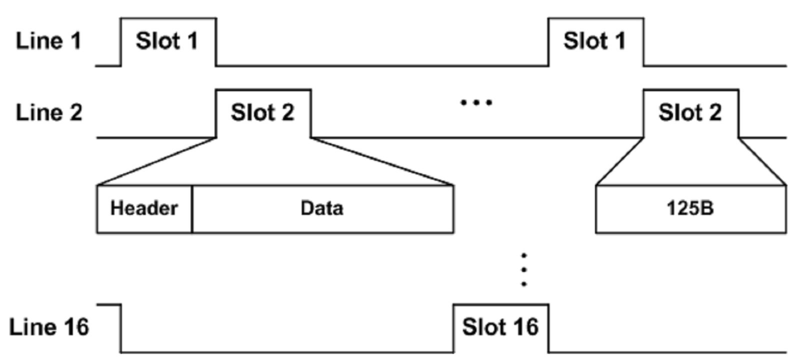


Figure 88—TDM for Signboard

VLC MUST support non-flickering and same brightness at each time slot and any time. To satisfy same brightness even though VLC data stream reduce the brightness to half, we need to increase of operating time per line such as 100% duty of 1ms = 50% duty of 2ms = 1ms on time per second. The simple frame structure makes increase the link efficiency.

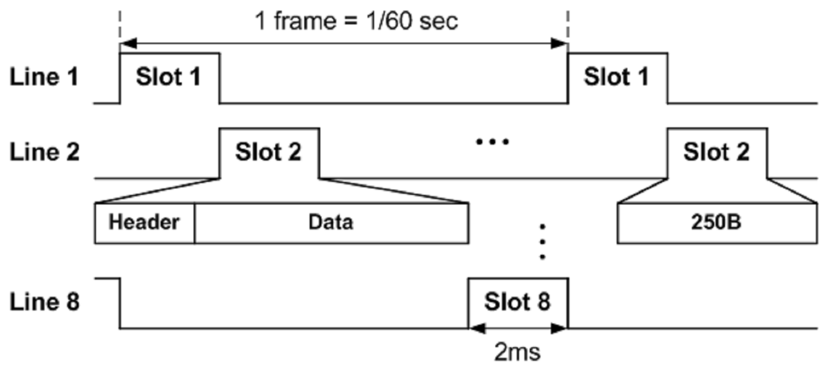


Figure 89—TDM 1 for Signboard

For third requirement, operating time of selected line is increased to 2ms. But 1 frame period is fixed, so we need to reduce time slot and divide led block so if we consider 1Mbps, 1 time slot is extended 2ms and can transmit 250bytes.

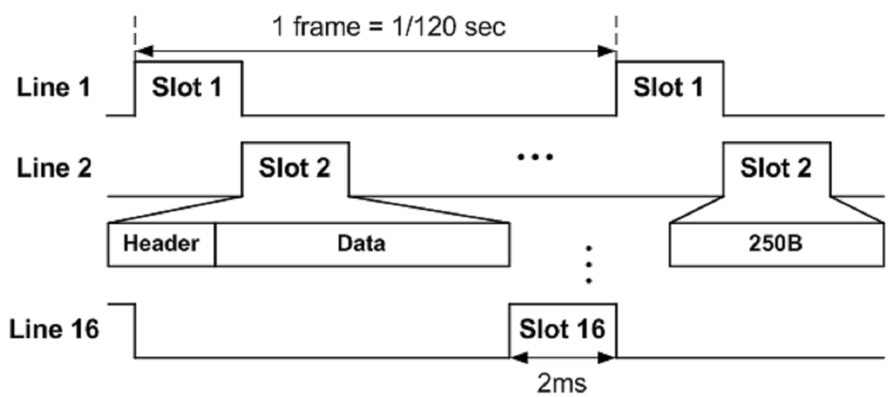


Figure 90—TDM 1 for Signboard

TDM2 is same at the incensement of operating time of selected line to 2ms. Difference is not reduced time slot but increase period. So frame rate is changed 60fps to 30fps. Whatever TDM1 or TDM2 is used, there are needed TDM for multiplexing at LED signboard.

The beacon is used to inform that the following frame is a TDM time slot: number of time slot and length of time slot. The TDM time slot can be allocated according to a service, a user, and QoS policy by multiple slot allocation according to service level. TDM Time slot consists of Beacon slot and Data slot. Beacon slot TS0 is a VLC header for compatibility information with source address and destination address, length field of beacon slot, service type(information broadcast service, data download service), and time slot information.

Data slot TS1 to end of TS is simple header with destination address (only for data download service) and no length field.

TDM and beacon make applications with a multiple broadcast service at Food court, department as follows; For example:

"TS1 (Korean), TS2(Japanese), … , TS16(information)

"TS1 (1'st floor), TS2(2'nd floor), …

QoS supported membership service with different data download speed by membership level can be applied as follows; For example:

"Gold member allocates 3 time slots

"Silver member allocates 2 time slots

"Bronze member allocates 1 time slot

Brightness of signboard can be controlled by modulation schemes such as VPM proposed in the PHY.

7.7.3.1 Incoming and outgoing superframe timing

On a beacon-enabled WPAN, a coordinator that is not the coordinator shall maintain the timing of both the superframe in which its coordinator transmits a beacon (the incoming superframe) and the superframe in which it transmits its own beacon (the outgoing superframe). The relative timing of these superframes is defined by the StartTime parameter of the MLME-START.request primitive (see 7.1.13.1 and 9.7.2). The relationship between incoming and outgoing superframes is illustrated in Figure 91.

The beacon order and superframe order shall be equal for all superframes on a WPAN. All devices shall interact with the WPAN only during the active portion of a superframe.

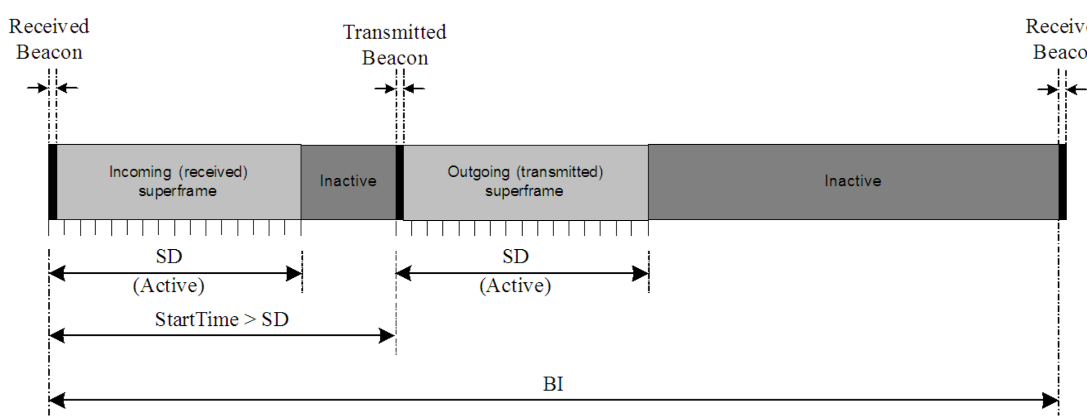


Figure 91—The relationship between incoming and outgoing beacons

7.7.3.2 Interframe spacing (IFS)

The MAC sublayer needs a finite amount of time to process data received by the PHY. To allow for this, two successive frames transmitted from a device shall be separated by at least an IFS period; if the first transmission requires an acknowledgment, the separation between the acknowledgment frame and the second transmission shall be at least an IFS period. The length of the IFS period is dependent on the size of the frame that has just been transmitted. Frames (i.e., MPDUs) of up to *aMaxSIFSFrameSize* octets in length shall be followed by a SIFS period of a duration of at least *macMinSIFSPeriod* symbols. Frames (i.e., MPDUs) with lengths greater than *aMaxSIFSFrameSize* octets shall be followed by a LIFS period of a duration of at least *macMinLIFSPeriod* symbols. These concepts are illustrated in Figure 92.

The random access algorithm shall take this requirement into account for transmissions in the CAP.

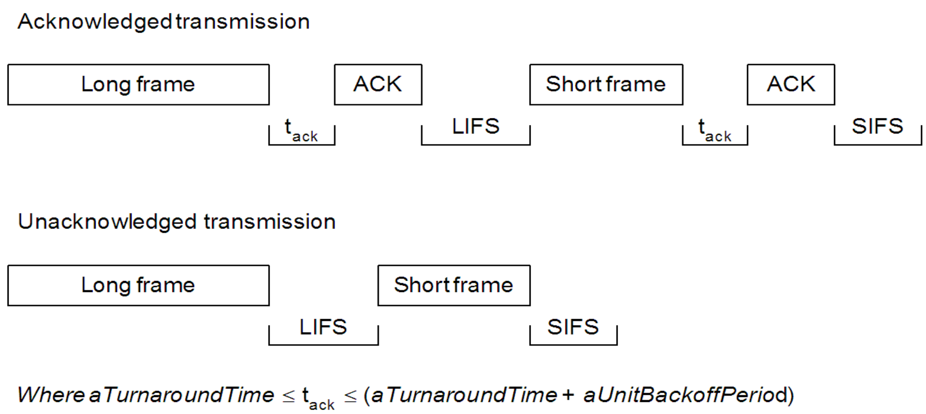


Figure 92—IFS

7.7.3.3 Random access algorithm

The random access algorithm shall be used before the transmission of data or MAC command frames transmitted within the CAP, unless the frame can be quickly transmitted following the acknowledgment of a data request command (see 9.7.7.3 for timing requirements). The random access algorithm shall not be used for the transmission of beacon frames in a beacon-enabled VLC WPAN, acknowledgment frames, or data frames transmitted in the CFP.

If periodic beacons are being used in the WPAN, the MAC sublayer shall employ the slotted version of the random access algorithm for transmissions in the CAP of the superframe. Conversely, if periodic beacons are not being used in the WPAN or if a beacon could not be located in a beacon-enabled WPAN, the MAC sublayer shall transmit using the unslotted version of the random access algorithm. In both cases, the algorithm is implemented using units of time called backoff periods, where one backoff period shall be equal to *aUnitBackoffPeriod* symbols.

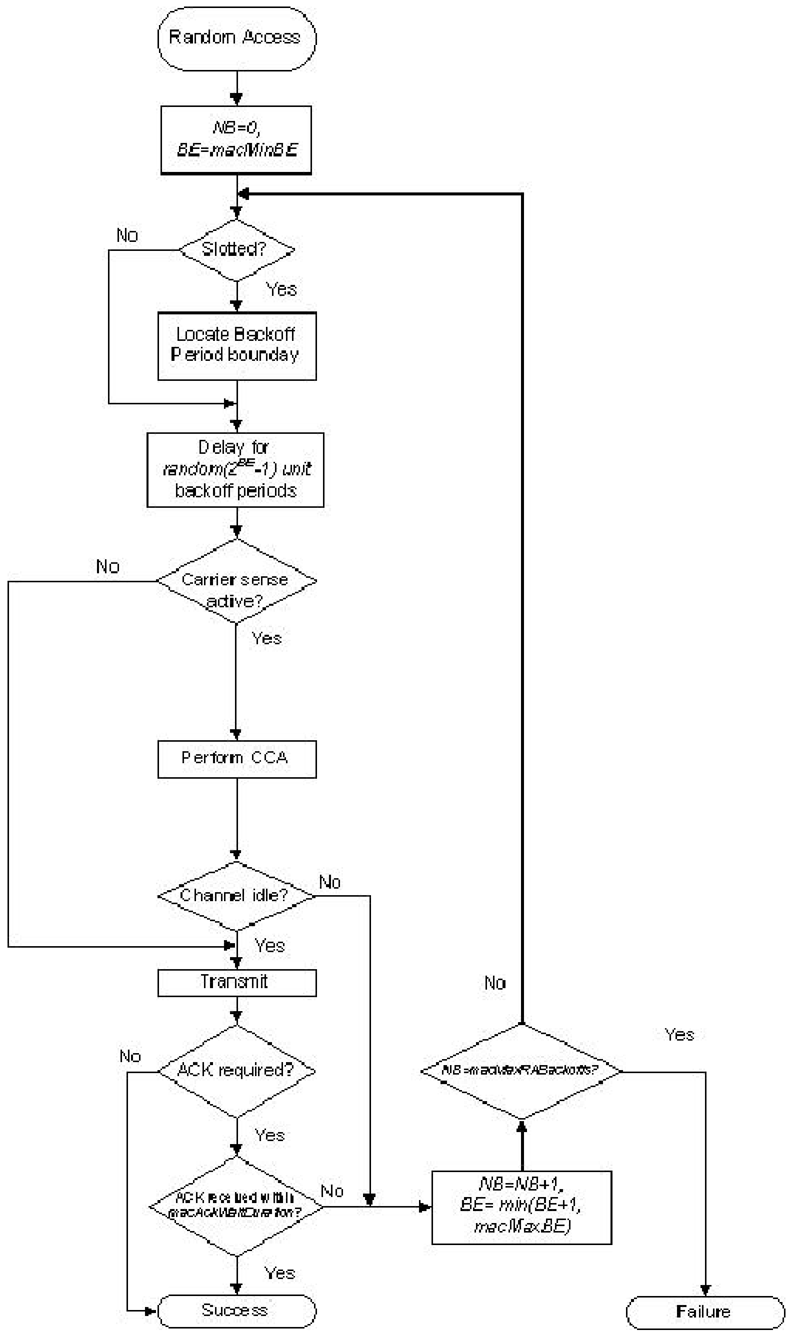
In slotted random access, the backoff period boundaries of every device in the WPAN shall be aligned with the superframe slot boundaries of the coordinator, i.e., the start of the first backoff period of each device is aligned with the start of the beacon transmission. In slotted random access, the MAC sublayer shall ensure that the PHY commences all of its transmissions on the boundary of a backoff period. In unslotted random access, the backoff periods of one device are not related in time to the backoff periods of any other device in the WPAN.

Each device shall maintain two variables for each transmission attempt: *NB* and *BE*. *NB* is the number of times the random access algorithm was required to backoff while attempting the current transmission; this value shall be initialized to zero before each new transmission attempt. The variable *BE* is the backoff exponent, which is related to how many backoff periods a device shall wait before attempting to access/ assess a channel. *BE* shall be initialized to the value of *macMinBE*.

Figure 107 illustrates the steps of the random access algorithm. The MAC sublayer shall first initiaize NB and BE for slotted random acccess then locate the boundary of the next backoff period. The MAC sublayer shall delay for a random number of complete backoff periods in the range 0 to $2^{BE} – 1$ [step (2)] and then request that the PHY perform a transmission or optionally a CCA. In a slotted random access system, the transmission, or CCA if active, shall start on a backoff period boundary. In an unslotted system, the transmission, or CCA if active, shall start immediately.

In a slotted random access system, the MAC sublayer shall ensure that, after the random backoff, the remaining random access operations can be undertaken and the entire transaction can be transmitted before the end of the CAP. Note that any bit padding used by the supported PHY (see 6.9.2.2) must be considered in making this determination. If the number of backoff periods is greater than the remaining number of backoff periods in the CAP, the MAC sublayer shall pause the backoff countdown at the end of the CAP and resume it at the start of the CAP in the next superframe. If the number of backoff periods is less than or equal to the remaining number of backoff periods in the CAP, the MAC sublayer shall apply its backoff delay and then evaluate whether it can proceed. The MAC sublayer shall proceed if the remaining random access algorithm steps, the frame transmission, and any acknowledgment can be completed before the end of the CAP. If the MAC sublayer can proceed and CCA is active, it shall request that the PHY perform the CCA in the current superframe. If the MAC sublayer cannot proceed, it shall wait until the start of the CAP in the next superframe and apply a further random backoff delay before evaluating whether it can proceed again.

If CCA is active and the channel is assessed to be busy, the MAC sublayer shall increment both *NB* and *BE* by one, ensuring that *BE* shall be no more than *macMaxBE*. If the value of *NB* is less than or equal to *macMaxRABackoffs*, the random access algorithm shall return to ???. If the value of *NB* is greater than *macMaxRABackoffs*, the random access algorithm shall terminate with a channel access failure status.



7.7.4 Visual link establishment with Color Packet Scheme

Color Packet is a packet to provide information such as device status and channel quality to the user intuitively. We can use Color Packet in VLC applications with various colors.

Examples of VLC applications with Color Packet are mobile to mobile VLC, VLC between toys, remote controller, and application with asymmetric data transfer.

When we use Color Packet in VLC, we can supply information to user intuitively and transfer messages to peer device. For examples, in communication between application and user, we can directly see the status information such as current step of communication procedure, data transmission quality (PER, BER), transferred file size or remained file size with our eyes by using color packet. For an example, in communication between device and device, device can transfer coarse link adaptation information to peer device by using color packet.

There are needed basic communication procedures for a color packet usage. MAC States consist of IDLE state, Connection state, Data Exchange state.

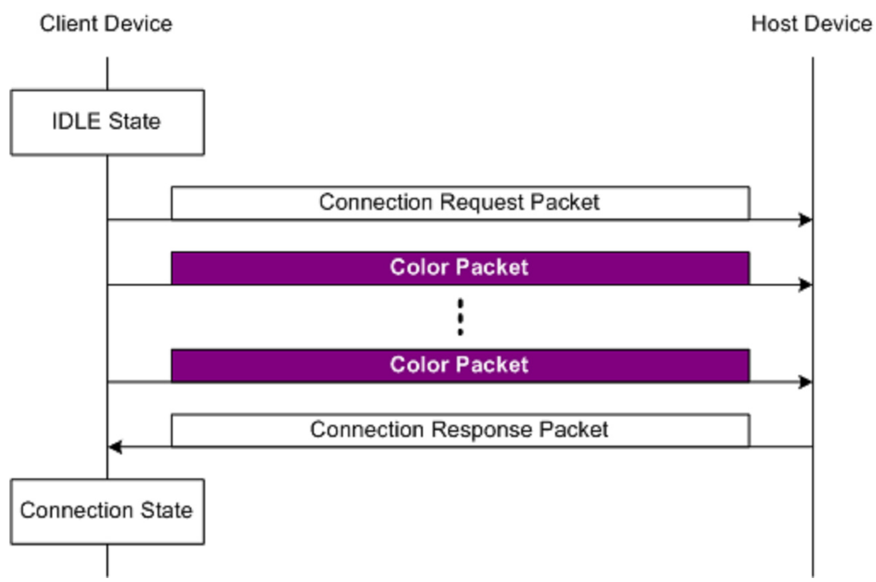


Figure 93—Step1 - A Color Packet Usage for Connection procedure

From Basic Communication Procedures, first Step1, Client Device transfer "Connection Request Packet" to Host Device. This step finished when Client Device receives "Connection Response Packet" from Host Device. Client device transfer purple color packet during transition between two states. User knows the current state of client device intuitively by purple color.

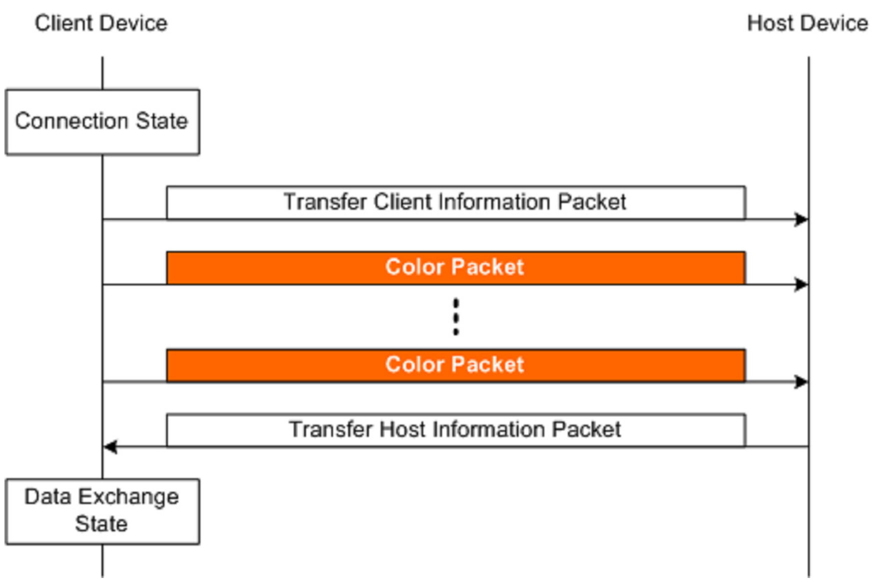


Figure 94—Step 2 - A Color Packet Usage for Exchange Information Procedure

At step2, client device state transit from connection state to data exchange state. During state transition, client device transfer Orange Color packet to host device. User knows client state intuitively by orange color.

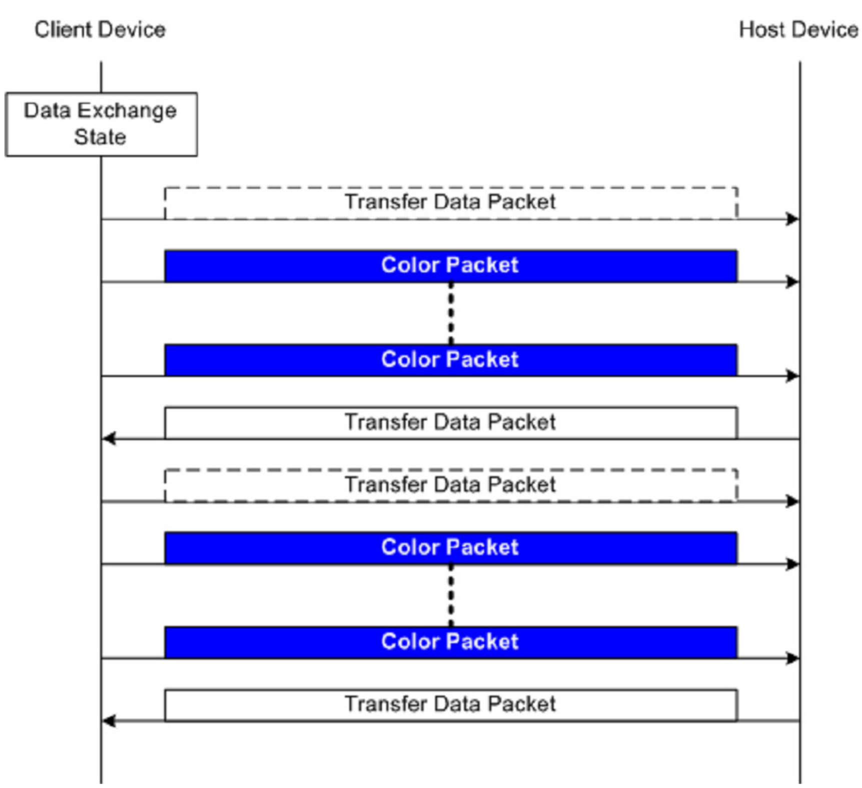


Figure 95—Step 3 - A Color Packet Usage for Transfer Data Procedure

At Step3, Client Device receive data packet from Host Device. Client Device held Data Exchange State while receiving data packet from Host Device. During Data Exchange State, client device transfer blue color packet to host device.

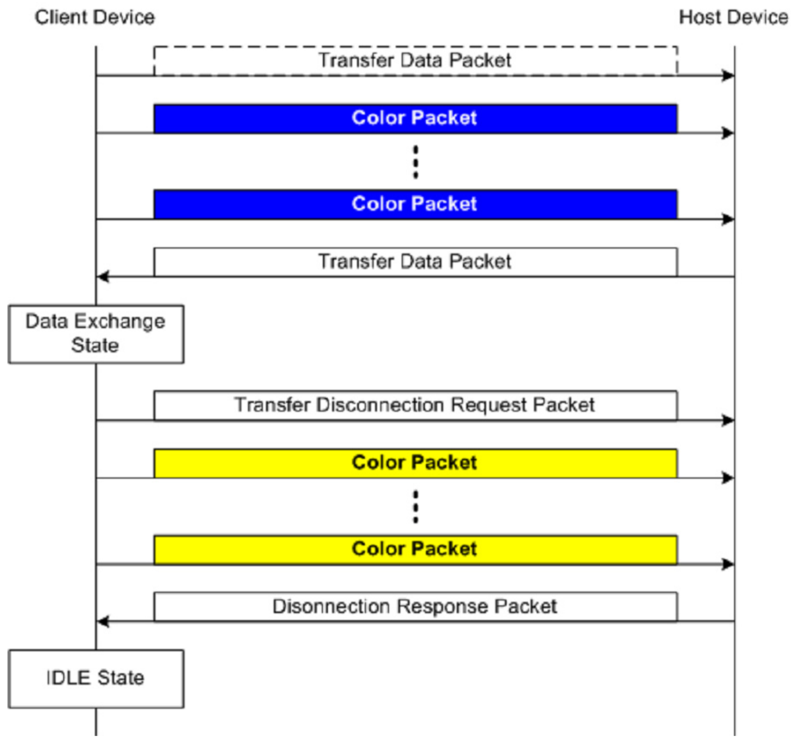


Figure 96—Step 4 - A Color Packet Usage for Transfer Disconnection Procedure

At last step, client device state transit from data exchange state to IDLE state. Client device transfer Yellow Color packet to host device during state transition. User can know the current step of communication procedure by using Color Packet during these communication procedures.

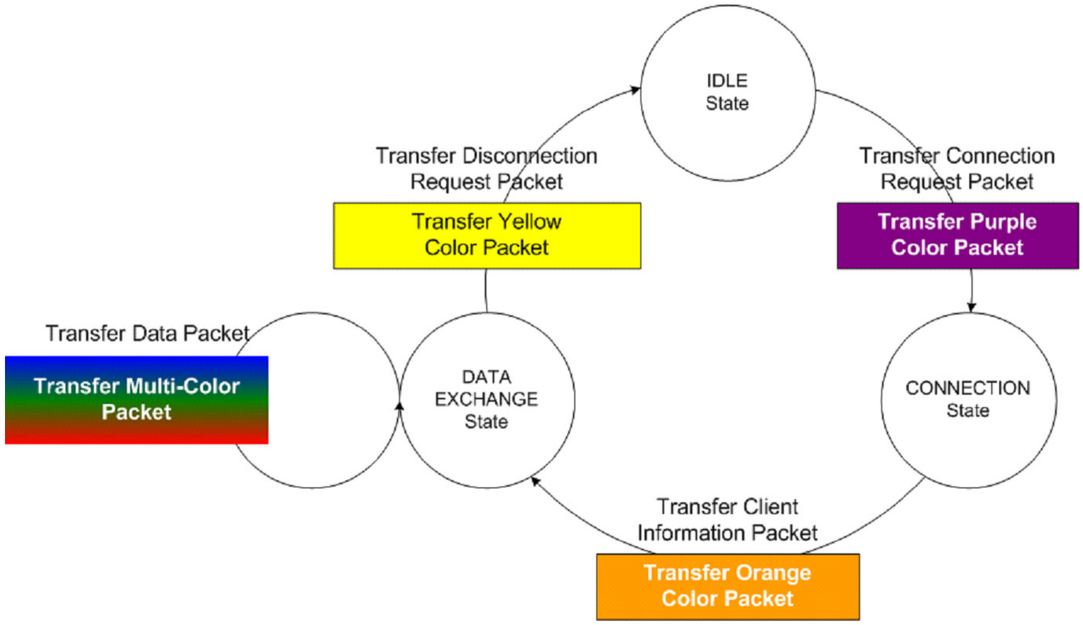


Figure 97—Color Packet Client State Diagram

This slide shows Client State Diagram in Previous Basic Communication Procedures. Each color packet is transferred during each state transition.

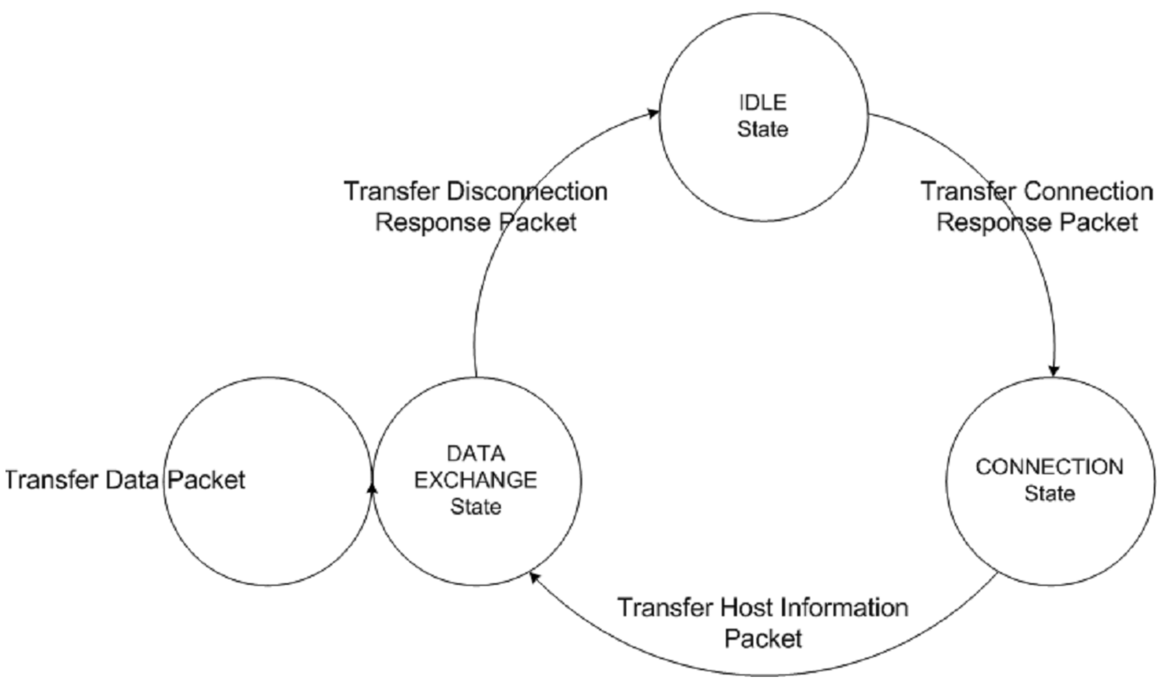


Figure 98—Color Packet Host State Diagram

In case of asymmetric data transfer, host doesn't transfer color packet to client for the transmission of data packet.

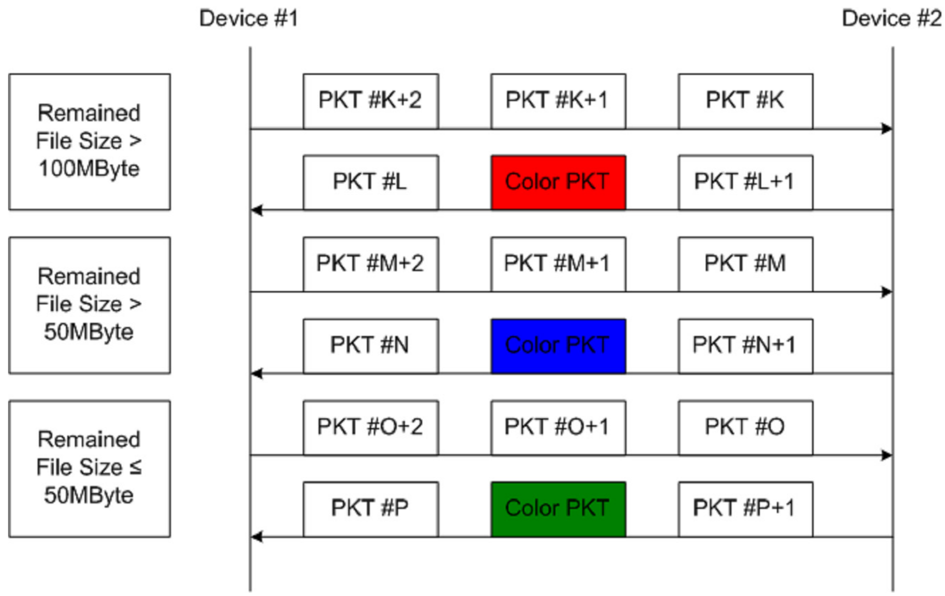


Figure 99—A Color Packet usage in File Transfer Application

This figure shows a color packet usage in file transfer application. User knows remained or transferred file size by using color packet in VLC.

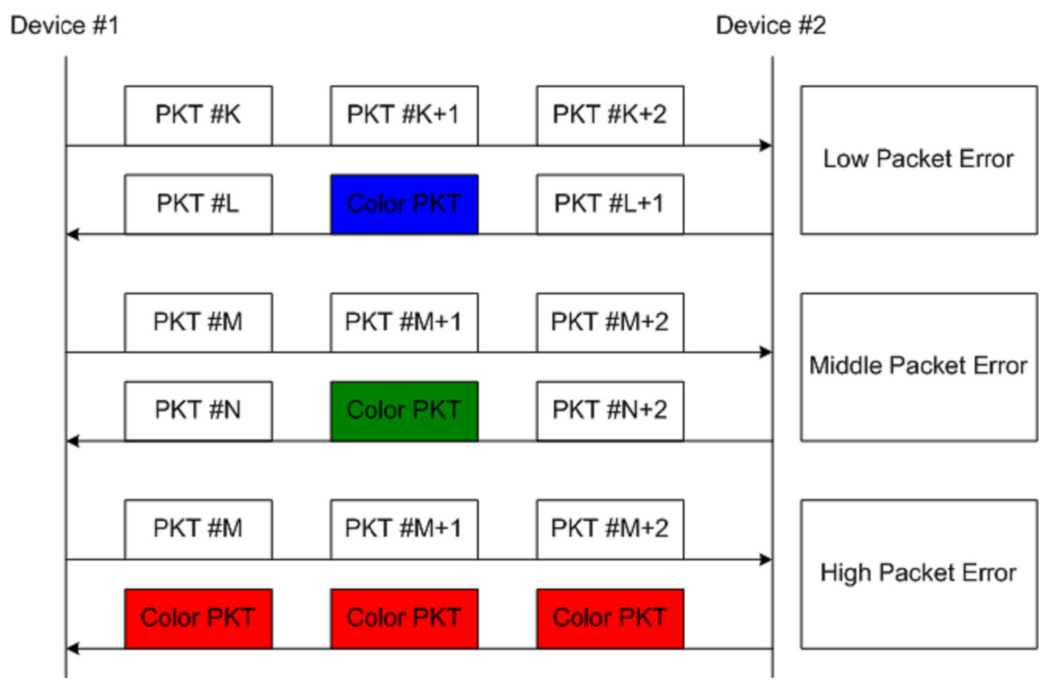


Figure 100—A Color Packet usage for Informing Data Transmission Quality to User

This figure shows a color packet usage when the color of color packet inform user to data transmission quality. User can know PER by using color packet in VLC. Low Packet Error shows green color packet.

Middle Packet Error shows blue color packet. High Packet Error shows red color packet. Until now, examples are to communicate between application and user.

(Table 1) Color Status Table in Coarse Link Adaptation

Color of Color Packet	Data Transmission Quality	Action Item
BLUE	$PER < 1e^{-2}$ *	Change higher modulation scheme
GREEN	$1e^{-2}* \leq PER < 1e^{-1}*$	Hold current modulation scheme
RED	$PER \geq 1e^{-1}*$	Change lower modulation scheme

* Different values according to application

This is a color status table to coarse link adaptation between device and device. User can know PER by using Color Packet. The Device received color packet knows it, too. Consequently, device can transfer coarse link adaptation information to peer device by using color packet. The device received color packet can change other data rate scheme by color status table.

Color Packet Header	Color Packet Pattern

(Figure 1) Color packet

7.7.4.1 Color Packet Structure

Color Packet Header must include next indicators. First color packet indicator means that transmitted packet is color packet, itself. Secondly, peer device information indicator show whether color packet include the message for peer device or not.

Color Packet provides the function of the visibility which is one of VLC's advantages. Color packet has the effects that informs intuitively to user without additional indicator. Device can use Color Packet to transfer the information messages to peer device. There is need an interface between Upper layer and MAC layer to support Color Packet Configuration.

7.7.5 Starting a PAN

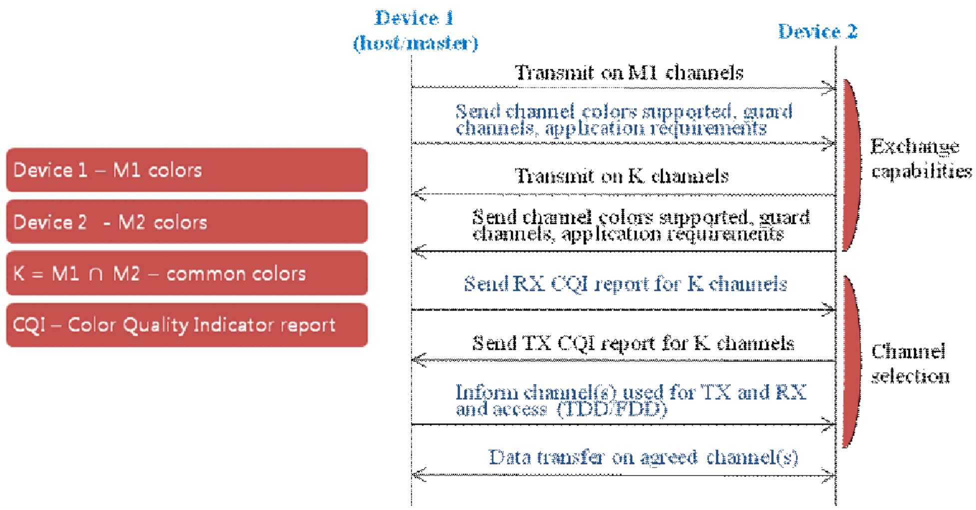


Figure 101—Starting a PAN

For a peer-to-peer network, the first device, which may be the host or master and initiates the communication, transmits on all supported M1 channels. Since there is independent hardware for each color at the transmitter and receiver, parallel transmissions are possible as long as guard color channels are not used for any particular color choice. Each device communicates the capabilities of each device and application requirements via the MAC and PHY capabilities IE provided. The MAC also reports the number of supported aggregated channels and the associated guard colors for each channel. Next, the other device attempts to receive and synchronize on all K channels shared between the devices. However, it may be able to receive on only 'x' channels, where 1 ? x ? K, due to interference with other light sources. The second device must receive on at least one channel in order to communicate. The K channels and device capabilities are obtained from the information mentioned in the information. Based on the interference energy from ambient light and the energy received during transmission, a CQI is calculated for all K channels. The second device then transmits on all K common channels to the first device. The second device also provides its supported channels, guard channels and application requirements as part of its capabilities information exchange. Next, the first device attempts to receive and synchronize on all K channels. It may receive on only 'y' channels, where 1 ? y ? K, due to interference. Since VLC is very directional, it is possible that 'x' and 'y' may be different. For example, if first device is closer to a window, it may receive more ambient light interference than the second device. The first device calculates its RX CQI for all K channels as well and transmits the CQI report back to the second device

Simultaneously, the second device calculates the CQI metrics based on the received information from the first device. Channels where reception is not possible or where other piconets are known to operate by the second device will be tagged unusable with a reception CQI of 0. The second device then reports this RX CQI for all K channels back to the first device

The master or initiating device, collects the information for the transmission such as the transmission and reception capabilities of the two devices, the CQI reports, the selected guard color channels for each channel and the requirements of the application. Based on this information, the first device determines a single or multiple channels for communication. The first device then reports the communication channels to the second device. Thus, at the end of this exchange, both devices have an estimate of the CQI for their transmissions that is most suitable for reception at the other end. From that point, both devices can communicate on the agreed channel or channels.

The support for CQI (color quality indicator) is provided in the PHY and shall be passed to the MAC via the MAC-PHY interface.

For a star topology network, the access point acts as the master for device discovery and association and uses the CAP for association requests and the beacon/management frames to broadcast its association grants.

Starting a PAN is only applicable to bi-directional communication modes.

7.7.6 Fast link recovery

In the star topology, a fast link recovery process may be triggered at the mobile node (MN) in the visible light communication. The trigger can be that the MN does not receive ACKs for a number of times given by a parameter N_ACKS set in the MAC command frame for fast link recovery. In the fast link recovery process, the MN may decide on its own to stop sending data. The MN may optionally send fast link recovery (FLR) signal repeatedly (within the resource allocated) to the infrastructure access point (AP) if the MN is plugged in with an adapter. Upon receiving FLR signal, AP sends a FLR response to the MN. After MN receives the response, the communication resumes. If there is both UL data service and DL data service, the MN may wait after stopping sending data.

Figure below shows an example of the process of MN stopping sending data based on the retransmission count.

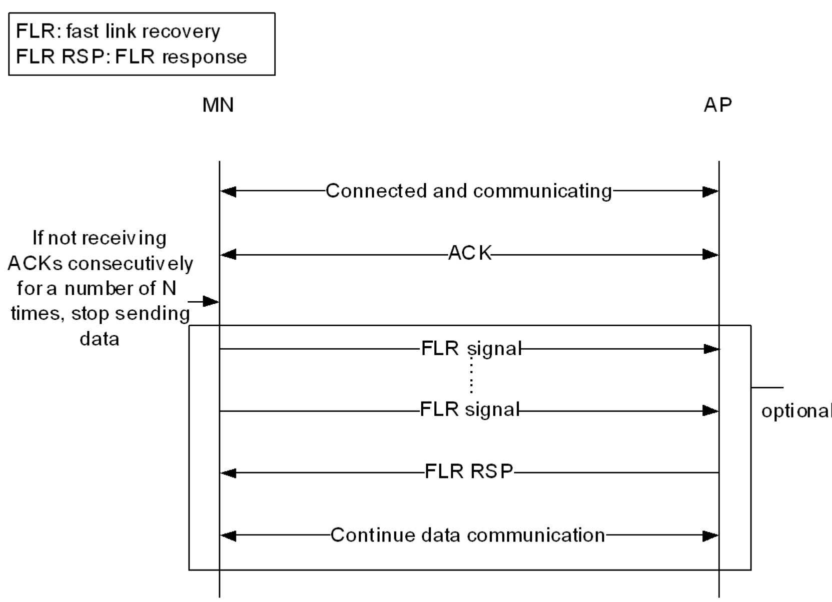


Figure 102—An example of the process of MN stopping data transmission based on the retransmission count, and triggering FLR.

In the star topology, a fast link recovery may be triggered at the access point (AP) in the visible light communication. The trigger can be that the AP does not receive contiguous ACKs for a number of times given by a parameter N_ACKS. In the fast link recovery process, the AP may stop sending data to the MN. The AP then sends fast link recovery (FLR) signal repeatedly to the MN. The AP may hold the uplink grant allocated to the MN. Upon receiving FLR signal, MN will send a FLR response to the AP. After AP receives the response, the communication resumes.

Figure below shows an example of the process of AP stopping sending data based on the retransmission count.

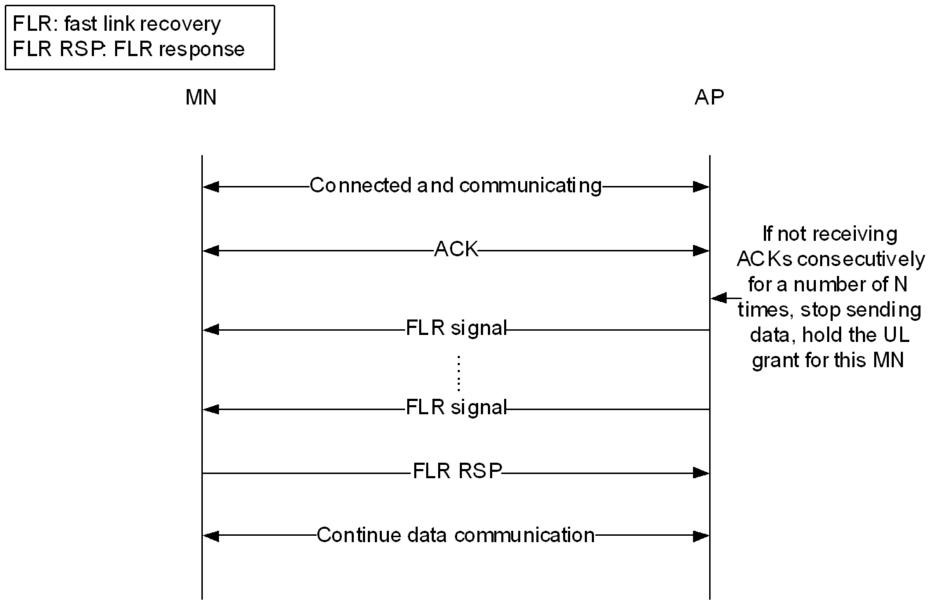


Figure 103—An example of the process of AP stopping sending data based on the retransmission count, and triggering FLR.

In peer-to-peer VLC, the devices let each other know their battery lives. If the conditions to trigger the fast link recovery process are satisfied, the device will further compare its own battery life with the battery life of its peer (the one it is communicating). If its battery life is shorter than its peer's, then it stops sending data, and wait. If its battery life is longer than its peer's, then it stops sending data, and start fast link recovery process. Battery life is indicated in MAC command frame structure When the fast link recovery is triggered, if the device has spare color bands, some or all of the spare color bands also start sending fast link recovery signals, to recover the link. The device then will choose a color band which gets the fast link recovery response to continue the communication.

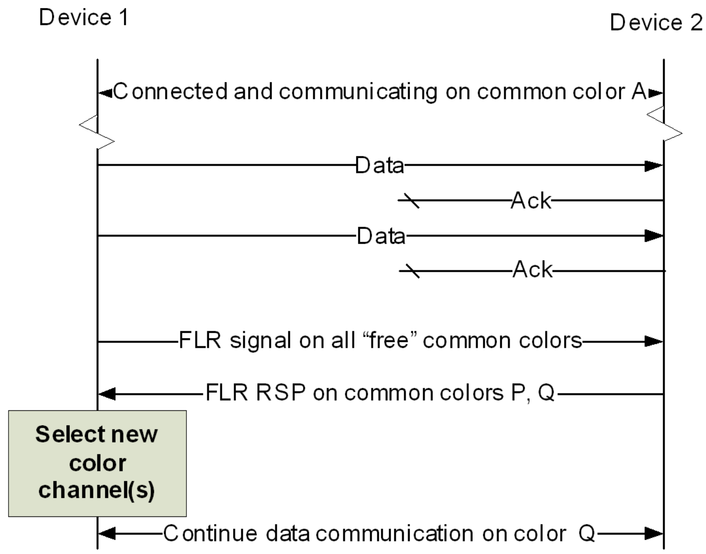


Figure 104—Flowchart of process for color band assisted fast link recovery

When the fast link recovery is triggered, if the device has other communication directions/angles, e.g., a light with multiple LEDs with different angles, some or all of the other angles also start sending fast link recovery signaling, to recover the link. The device then will choose an angle which gets the fast link recovery response to continue the communication. The process of fast link recovery on other directions/ angles can be made parallel in multiple directions or successive (i.e., one direction after another). The direction is indicated in the link recovery mechanism provided by the command frame structure.

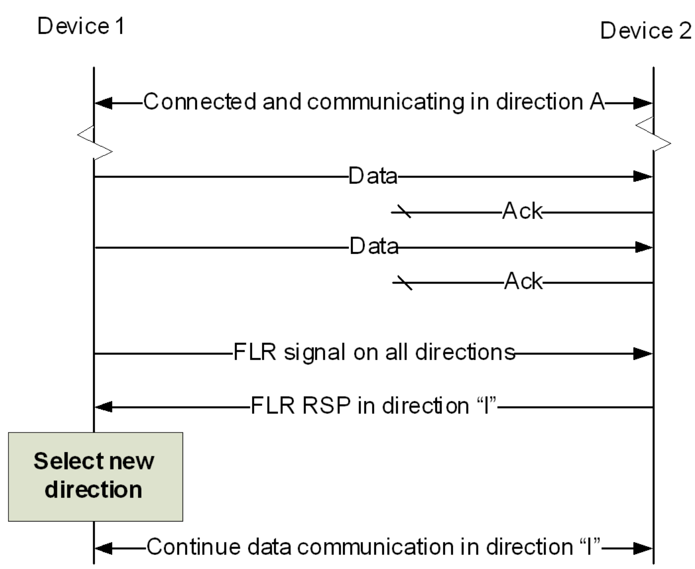


Figure 105—Flowchart showing process of multiple angles assisted fast link

7.8 Multiple channel resource assignment

In order to support system capacity enhancement of multiuser communication and interference avoidance, VLC system can apply multi channel application. This channel can be assigned to one user and multi user without user limitation. If multiple channels are used in VLC, multi channel hopping also can be used for interference avoidance. Also this multi channel does not limit R/G/B only. If more channels are required in VLC, then more channel than R/G/B can be assigned in VLC system. In Figure 118 is one example of the multiple channels. In practice, there is no limit the number of multiple channels over R/G/B.

7.8.1 Multiple channel information

If AP(Access point) uses this multi channel application in Figure 118, this multiple channel means different wavelength can be used in VLC system. By using multiple channels, VLC system can support interference avoidance of adjacent user and cell.

In VLC system, MS(Mobile Station) can receive Src_multi_info from AP in management payload field. Management payload table was defined in 7.9.1. If AP want to use multiple channel application, AP transmit Src_multi_info to MS, then MS response as Des_multi_info because AP do not knows affordable multiple channel of MS. This multiple channel can be supported by MS Des_multi_info. In order to apply multiple channels, AP must search for available channel status. After searching of AP, then AP define Src_multi_info bit.

If AP wants to do not use multiple channel application in VLC, then AP transmits Src_multi_info '000' setting. It means that multiple channels are not used in VLC, conventional VLC system is set by Src_multi_info '000'.

In order to support this multiple channel, initial channel was fixed for AP and MS communication. It will be depending on initial system setting or Src_multi_info '00000'. After AP and MS initialization, multiple channels can be applied.

If AP does not use multiple channel service, bit '00000' in table 1 will be transmitted to MS. Also MS can response as Des_multi_info. This information is to notify MS affordable multiple channel resource. This means that MS do not use multiple channels according to MS environment (e.g. MS do not support multiple channel function by H/W limitation, interference situation of MS environment). MS can transmit information about possible multiple channel assignment. MS must transmit affordable resource statues of multi channel to AP based on Src_multi_info. AP is assigning resource of multiple channels to MS with searching available AP multi channel resource.

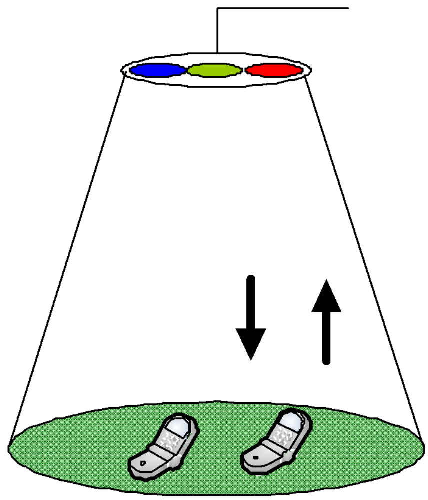


Figure 106—Channel assignment of MS information

channel	bit	R	G	B	
1	00000	O	O	O	No multiple channel mode (conventional VLC)
2	00001	O	O	X	
3	00010	O	X	O	
4	00011	X	O	O	
5	00100	O	X	X	
6	00101	X	O	X	
7	00110	X	X	O	
8	00111	X	X	X	

Table 73—Channel assignment of MS information

7.8.2 Channel hopping for interference avoidance

7.8.2.1 Hopping pattern information

This scheme will be used to avoid interference of other user. MS(Mobile Station) can receive H_pattern from AP in management payload field. Management payload table was defined in 7.9.1. Also this hopping pattern does not limit R/G/B like as multiple channels. If multiple channel do not used in VLC, also Hopping pattern do not applied in VLC system

In order to avoid other user interference, AP assigns hopping pattern type to MS. If MS receives H_pattern from AP, MS can operate and hop based on hopping pattern with pre assigned pattern. This pattern can be applied with fixed in VLC communication system in order to avoid adjacent cell or adjacent AP interference. In case of the sam time slot in VLC adjacent cell, If adjacent cell use R/G/B then, interference will be occurred among adjacent cells. In order to avoid interference and increase system capacity, pre assigned hopping pattern do not gives adjacent cell interference.

In Figure 119, If a certain optical source uses HP1 (00001) and other optical source in adjacent cell uses HP2 (011), then hopping pattern application in adjacent cell is that HP1 operates R in first frame or time slot, B in second frame or time slot, G in third frame or time slot, but HP2 is operating at G in first frame or time slot, G and R in second frame or time slot, R and B in third frame or time slot. This mechanism can avoid interference between optical sources each other. Also hopping pattern application does not limit one frame or one time slot. Many frame or time slot based is fine for application and more than R/G/B is fine to hopping pattern. When Src_multi_info is 00000, then no H_pattern application

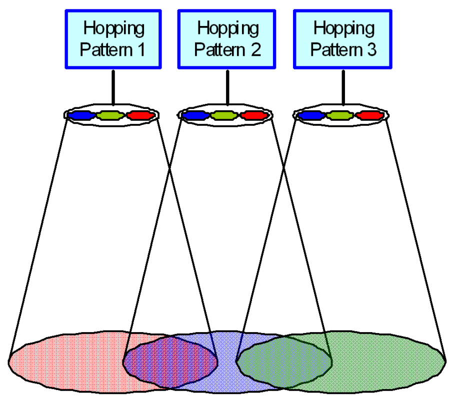


Figure 107—Hopping pattern assignment

Table 74—Hopping Pattern Assignment

Pattern set	00001	00011	00101
Frame/time slot	HP 1	HP 2	HP 3
1	R	G	B
2	B	G/R	B
3	G	R/B	G
4	G/R	B	G/R
5	G/B	R	G/B
6	R/B	G	R/B
7	G	B	R
8	B	R	G
9	R	G/B	R

Figure 2 shows hopping pattern assignment in multiple channels. Table 2 expressed hopping pattern example for applicable to VLC. If AP assign pattern '00001' to MS by using H_pattern, then MS's frame or time slot moves according to hopping pattern. Also one hopping pattern can be assign to one user and multiple hopping patterns can be assigned to one user

7.9 Concept of VLC cell and mobility

There may be a need to support link switching due to physical movement or interference. Mobility can be of two types: physical and logical. Physical mobility occurs when the VLC device M1 changes its position due to the movement within the coverage area of infrastructure I1 while logical mobility occurs when the device M1 changes its communication link from a link with infrastructure I2 to one with infrastructure I3 due to interference or deliberate channel switching.

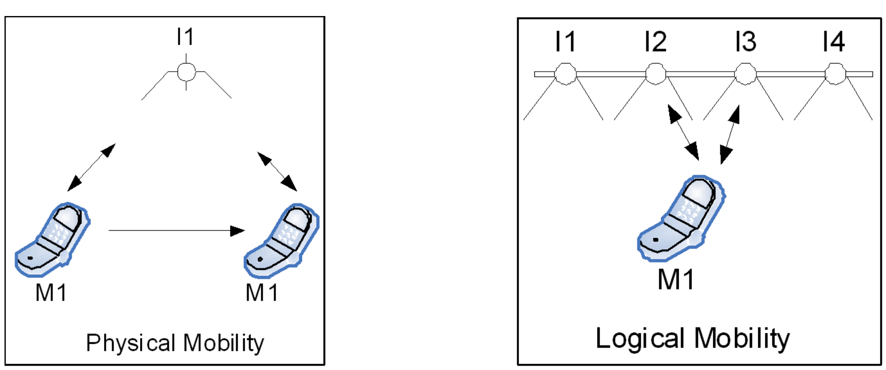


Figure 108—Physical and logical mobility

7.9.1 Physical mobility by boundary alarm

Mobility in VLC can be used as user dependent notification. In management payload field, mobility related information is MS_ID, Cell_info, B_info, S_info, # of time slot. This mobility is supporting based on virtual time slot assignment basis. MS_ID stands for each MS ID and Cell_info is used for Cell ID discrimination. S_info is used for time slot assignment information based on MS_ID. B_info is to notify time slot assignment in cell boundary and previous time slot return information.

Table 75—[Ed. Note: what is this table about? I need a better copy.]

octets: 7	1	xx
MHR fields	Command Frame Identifier	Mobility fields

(Table 1) Mobility notification command

Table 76—What is the name of this table?

Management payload field	Bit	usage
Src_multi_info	5	source multiple channel resource assignment 00000 : No multiple channel application
Des_multi_info	5	destination multiple channel resource assignment
H_pattern	5	multiple channel hopping when Src_multi_info is 00000, then no H_pattern application
VF_info_type	1	Visible Frame transmission 1 : Receiver VF transmission 0 : Non receiver VF transmission (do not use VF in receiver)
G_cell_ID	10	granular cell assignment
Fractional_Src	2	frame source notifications
Mode_type	2	multicast,broadcast, uincast
S_Release_slot	5	start and release slot for broadcast
special mobility	?	request special mobility
MS_ID	10	terminal ID or usre ID
# of time slot	5	number of time slot
Cell_info	10	Cell ID(PD_ID) or AP ID
B_info S_info	2 5	cell boundary information virtual time slot assignment

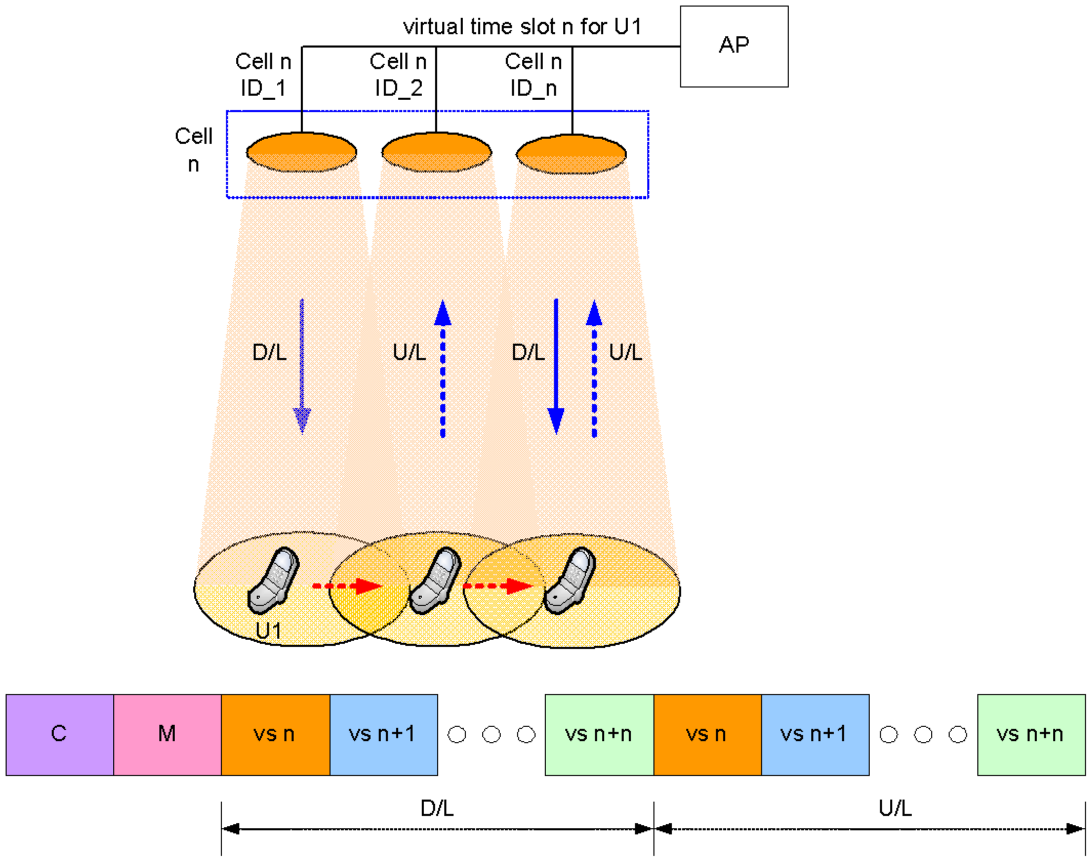


Figure 109—VLC mobility

In VLC communication system, each optical source has a function of transmitter (like as LED/LD) and receiver (like as photo detector). In order to support multi user communication and high system capacity, VLC can apply cell configuration. One cell and many cells can connect one AP (Access Point). Also Each user in a cell uses different time slot by resource assignment from AP(or APs controller). Different time slot assignment can remove interference of cells. Figure 121 shows one of the VLC system cell configurations. A VLC cell definition can be designed as some optical source groups. A cell definition is granular group of each VLC optical source. This optical source is composed of transmitter and receiver. Also each optical source in a cell has each cell ID like as Figure 121. For MS mobility support in VLC, large cell size of VLC can give easy mobility of MS, but large cell size decrease system capacity in case of multi user service based on TDD/TDMA communication system. Also small cell size increase system capacity. But small cell size will give a lot of resource assignment and resource change (like as cell hand off) etc. Cell size in VLC must be considered as aspect of system capacity.

In Figure 121, some optical source was grouped as a cell area(a Cell n). If U1(user 1) moves to next optical source area(from Cell n ID_1 to Cell n ID_2) with virtual time slot vs. n(vs n) assignment by AP(Access Point), MS and AP can communicate with D/L(downlink) and U/L(uplink). Also AP can detect MS position in a cell by using optical Cell ID because MS transmit U/L signal(like as data ack or response) to Cell ID(optical source). Then MS mobility can detected in AP by using Cell n IDs.

Figure 122 shows resource assignment by using boundary alarm information.

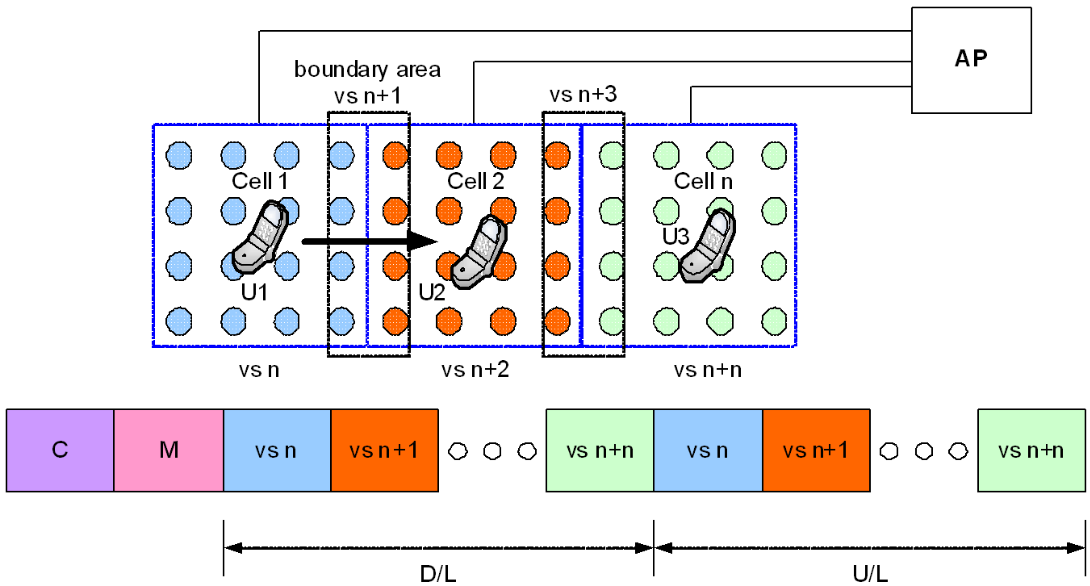


Figure 110—VLC resource assignment

Figure 83 shows U1 mobility and resource assignment from cell 1 to cell 2. In cell 1, U1 has vs n. vs n+2 time slot was assigned to U2 in cell 2. vs n+n time slot is for U3 in cell n. cell boundary can be defined as each cell edge area in figure 1.

If U1 is approaching cell 1 edge, then AP can detect U1 uplink signal at boundary area of cell 1. Optical sources of boundary area have each cell 1 IDs and cell 2 IDs with vs n+1 resource assignment. If U1 was detected in boundary optical source area between cell 1 edge and cell 2 edge, then boundary area optical source transmit boundary alarm information(B_info based on MS ID) to U1 and optical source can assign new virtual time slot vs n+1 to U1 simultaneously. Time slot resource vs n+1 will not be used in cell 1 and cell 2 for cell interference avoidance. In boundary area, U1 can use vs n and vs n+1 for communication. The management payload field has user specific information. In boundary area, optical sources are composed of Cell 1 edge and Cell 2 edge. Also MS can discriminate that what is optical source alarm of Cell 1 and optical source alarm of Cell 2 because boundary area optical source of cell 1 edge and cell 2 edge transmit the same B_info, and S_info, MS ID, Cell_info simultaneously. Although the same B_info, and S_info, MS ID, Cell_info is the same MS can discriminate optical source of Cell 1 and Cell 2.

If U1 continues movement from boundary area to cell 2, then U1 can detect cell 2 optical source alarm in boundary area. In this case, U1 will return previous time slot resource vs n automatically, because time slot vs n resource was assigned in cell 1. this returning action will give a chance to resource assignment of other MS without previous time slot returning notification of AP. If U1 reaches in cell 2, U1 will communicate with AP by using vs n+1 only. Because U1 returned vs n. Also If VLC cell is split like as cell 1 and cell 3, then the same time slot can be assigned to other user because of no cell interference based on TDD.

The other automatic returning action of previous time slot resource vs n is that U1 do not detect boundary alarm information in cell 2. This returning action depends on boundary alarm information detection in U1. This way of retuning previous time slot is that MS in boundary cell is detecting optical source Cell_ID, If Cell_ID was changed in MS, then MS returns previous resource.

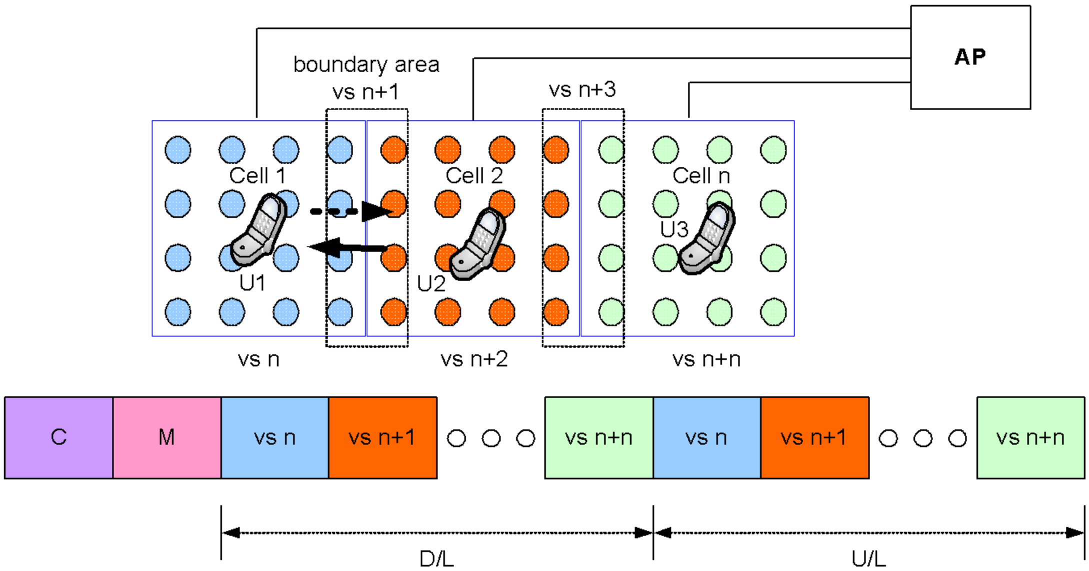


Figure 111—VLC resource assignment

Figure 123 shows that U1 was returned to previous cell 1 after vs n+1 time resource assignment from AP. This case is the same Figure 122. U1 returns vs n in Cell 1 and U1 uses vs n+1.

Figure 124 shows resource assignment in multi cell overlapped edge area

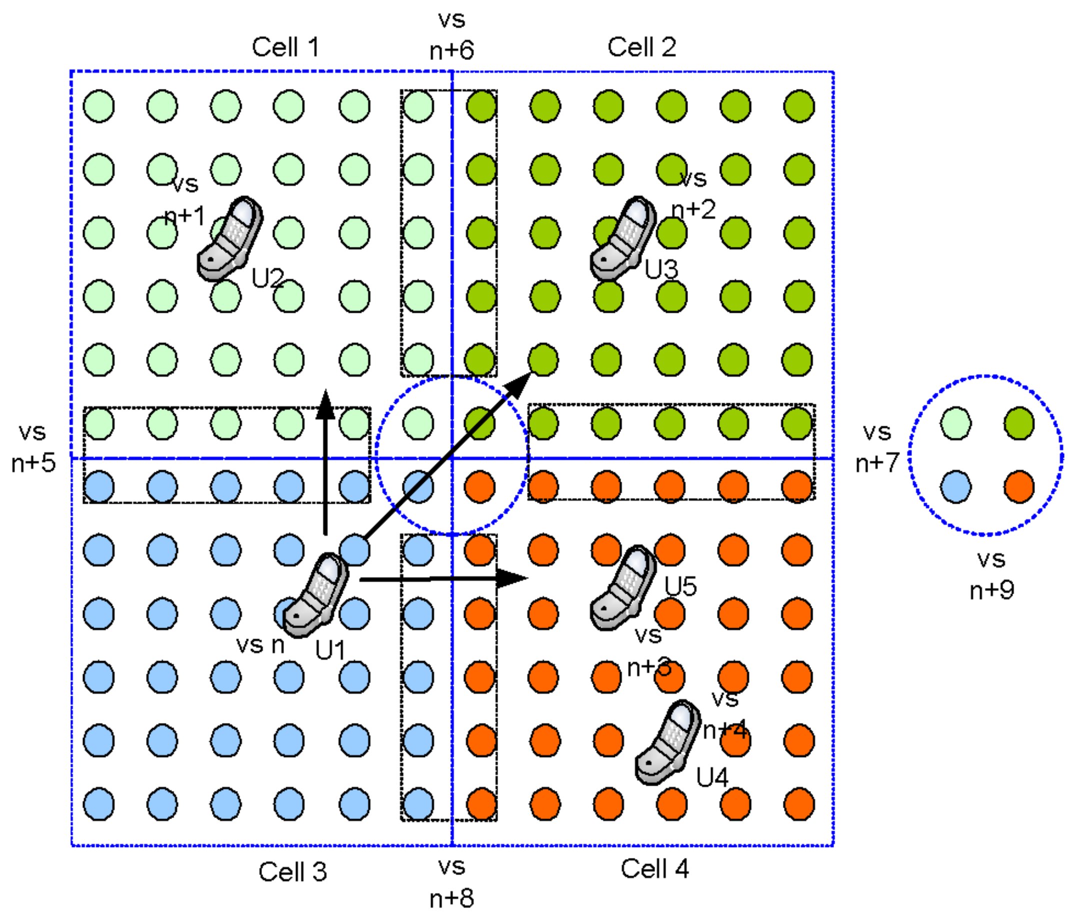


Figure 112—Multi cell overlapped edge resource assignment

In Figure 124, If U1 moves from cell 3 to cell 1, there are three overlapped areas as Figure 124. When U1 want to move cell 2 area, U1 must pass cell 1 and cell 2, cell 4 overlapped are.

In order to move without cell interference, multi boundary optical source area will assign a new virtual time slot. If U1 moves to multi cell boundary with vs n time slot, U1 can receive boundary alarm information in multi cell boundary. Also multi cell boundary area must assign time slot vs n+9. vs n+9 will not use in Cell 1, Cell 2, Cell 3 and Cell 4.

Figure 125 shows same optical source ID assignment in a cell.

7.9.2 Same optical source ID assignment in a cell

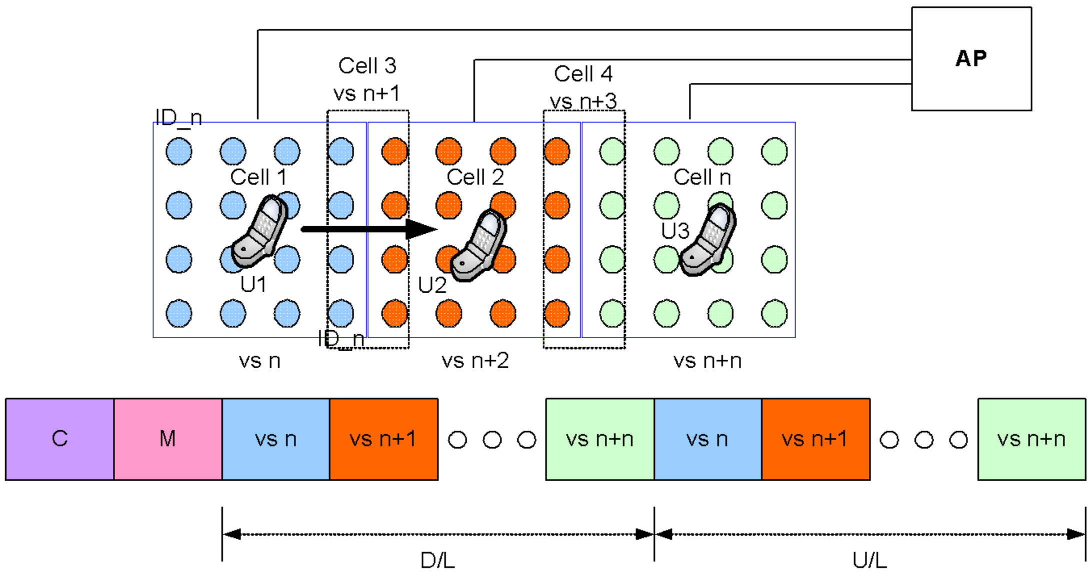


Figure 113—Same optical source ID assignment

Figure 125 shows same optical source ID assignment in a cell. The same ID was assigned to optical sources in each cell but different cell ID in each boundary area can be assigned for mobility support. In this case optical source cannot detect U1 movement of position because the same optical source ID was used in a cell. If U1 moves from cell 1 to cell 2, optical source in a cell cannot detect U1 movement and when U1 is approaching boundary area, then optical source can detect U1 movement because cell 1 and boundary area are use different source ID. This function is only for reduction purpose of Cell ID.

7.9.3 Fractional resource assignment

Spatial mobility can be supported in VLC system. Figure 126 shows an example of fractional resource assignment. This resource assignment is to use for non fixed cell based configuration application. If fractional resource assignment can have freely cell configuration. In case of all optical resources having each Cell ID, each MS position can be detected at each optical source ID. AP can detect MS position and can assignment non limited cell with time slot. Second method to support spatial mobility is by checking ACK and NACK signal. When NACK signal is received in AP then AP extend visible light active area. With process ACK signal, AP judges whether ACK signal is received from MS within visible light active area. If ACK signal is received, AP corrects visible light active area with reception point as the central point.

This has option for dynamic cell configuration and efficient resource assignment. If VLC system select fractional resource assignment (Fractional_Src : 1)for cell configuration, then VLC system will operate like as Figure 126. If U1 transmits initial access, optical source of AP can detect U1 signal power. If one of the optical sources is detecting the strong power, then AP composes a cell configuration based on the strong optical power receiver. U1 will be assign virtual time slot vs n and AP defines a certain cell area configuration for U1. Other area of full cell can be assign different time slot in a cell area for other user service. It will increase system efficiency. Also each user does not have interference because each MS has different time slot for communication. If Fractional_Src is set 11, then Fractional resource assignment is supported. If 00 is set, then Fractional_Src do not use in VLC.

This can accommodate many users in a certain area without cell planning. How to make cell was defined in 7.9.4.

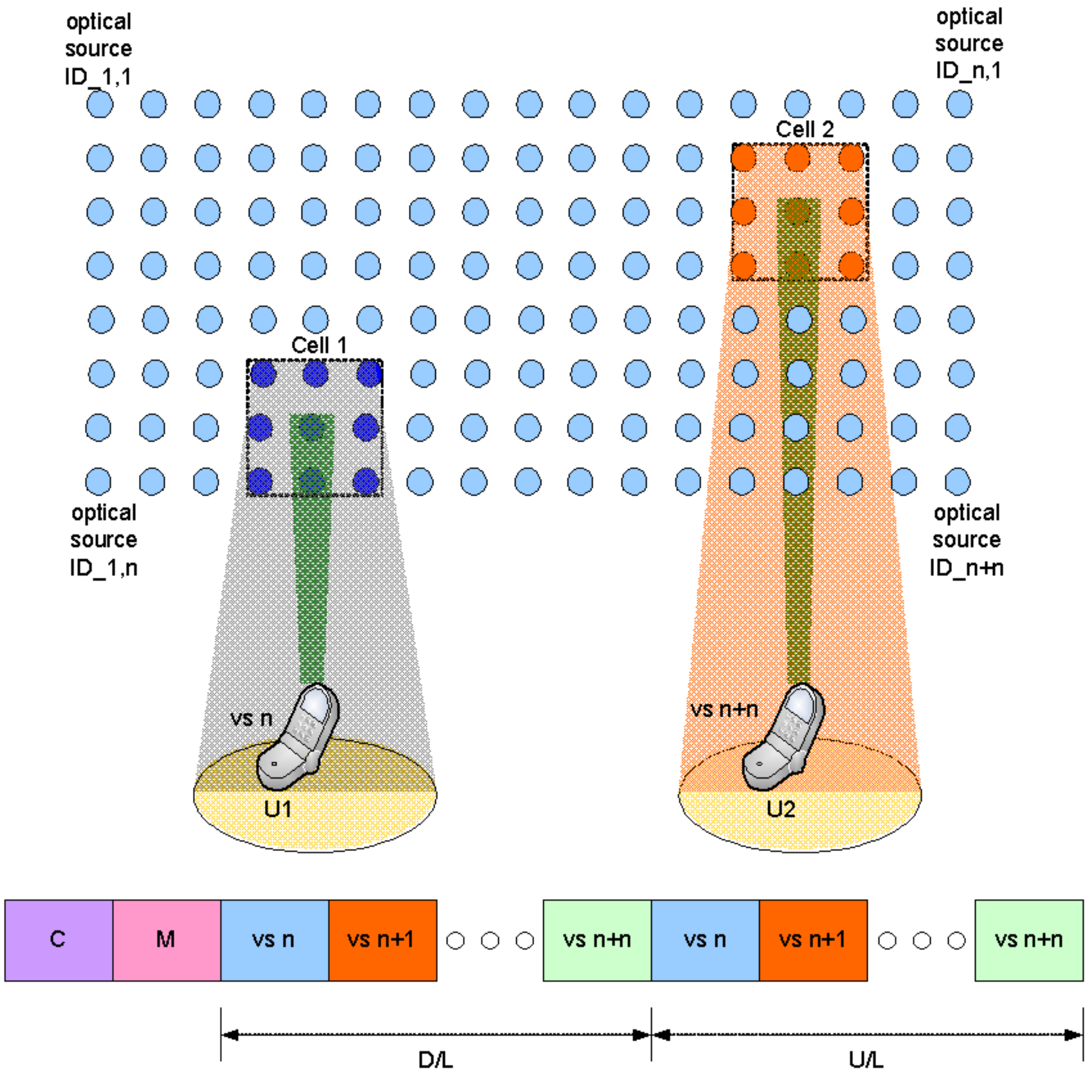


Figure 114—Fractional resource assignment

7.9.4 Granular cell configuration and resource assignment

This is used for cell size definition and can support dynamic cell mobility. In figure 127, cell size can be defined by using G_cell_ID. If G_cell_ID is set as 00000 00001, then AP makes a cell right, left, top and bottom direction of 1 optical source sised cell like as U1 in figure 127. Figure 127 gives an example for G_cell_ID (00001 and 00010) cell definition. If G_cell_ID is set as 00000 00010, then a cell configuration can be shaped as U2 service area. If G_cell_ID is set 00000 00000, granular do not use in VLC.

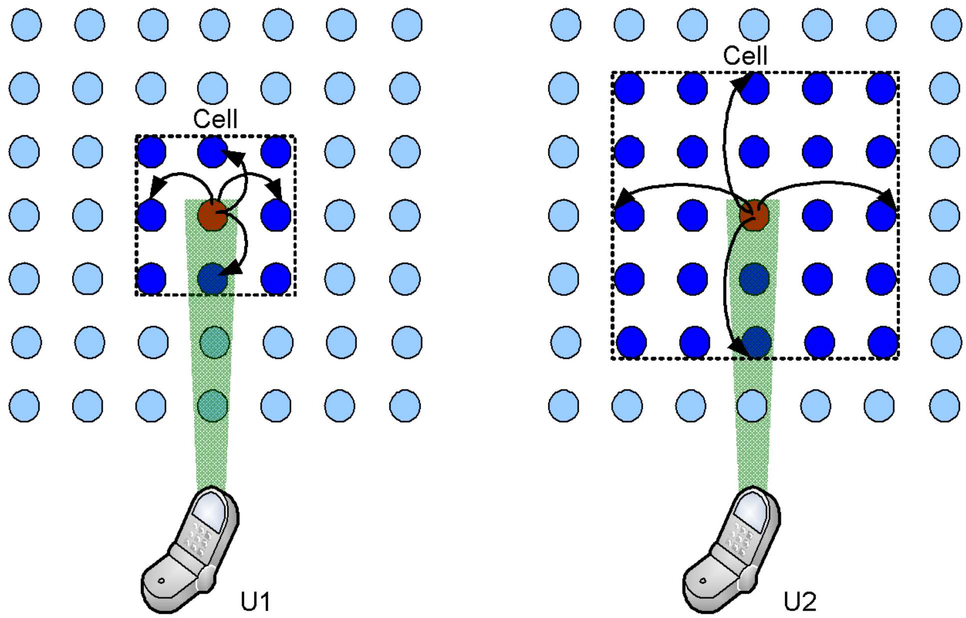


Figure 115—cell definition by using G_cell_ID

7.9.5 Granular cell resource assignment for mobility

Figure 128 shows an example of U1 movement to U2 direction. U1 and U2 can communicate without interference because U1 (cell 1) and U2 (cell 2) use different time slot. This shows cell window movement for each MS movement. In Figure 129 shows cell window movement mechanism. If U1 moves from a certain area to U2 area, AP compares U1 position of MS uplink signal based on different optical ID. If MS has movement, then AP changes cell window according to MS movement direction based on G_cell_ID size. When U1 is moving to other area, optical source ID is also changed.

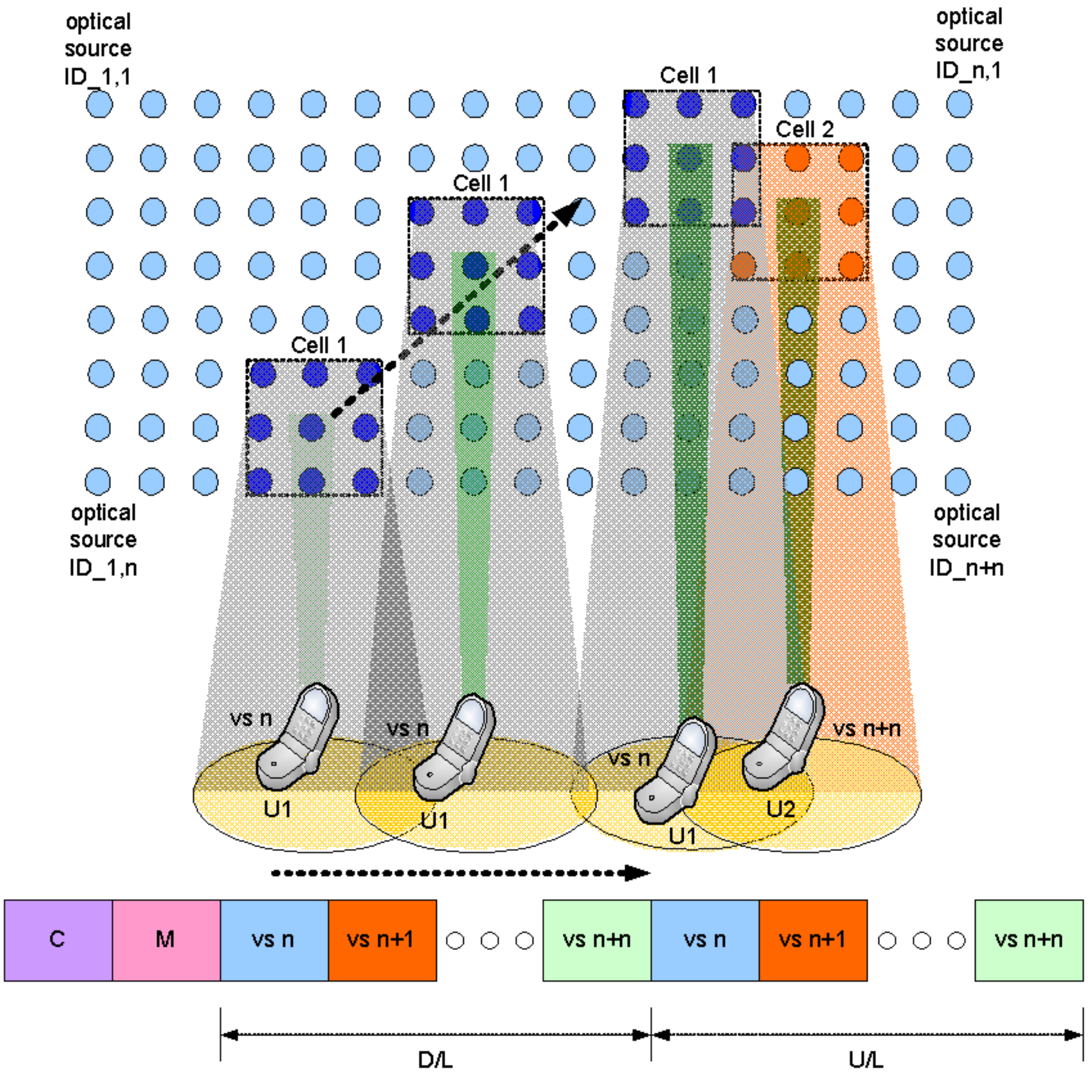


Figure 116—Resource assignment for granular cell

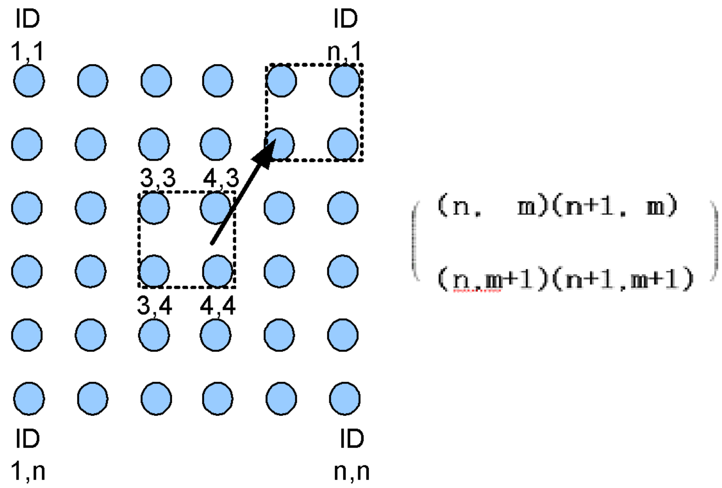


Figure 117—Optical source ID assignment

8. Visibility support

8.1 Necessity

The standard supports visibility for the following purposes:

"Alignment (Device discovery, negotiation, connection)

"Visible guiding for user alignment

"Infrastructure continuous light output

"Blinking for unexpected interference, disconnection warnings

8.2 Visibility pattern

The MAC passes the visibility pattern requirement to the PHY layer via the MAC-PHY interface. Sending a visibility pattern is a mandatory requirement for infrastructure during idle or receive operation to ensure continuous illumination. Sending a visibility pattern is optional for the mobile device.

8.3 Extended preamble mode for visibility

The MAC provides an extended preamble mode for visibility. The advantage of this mode is to provide additional time for synchronization while simultaneously providing visibility.

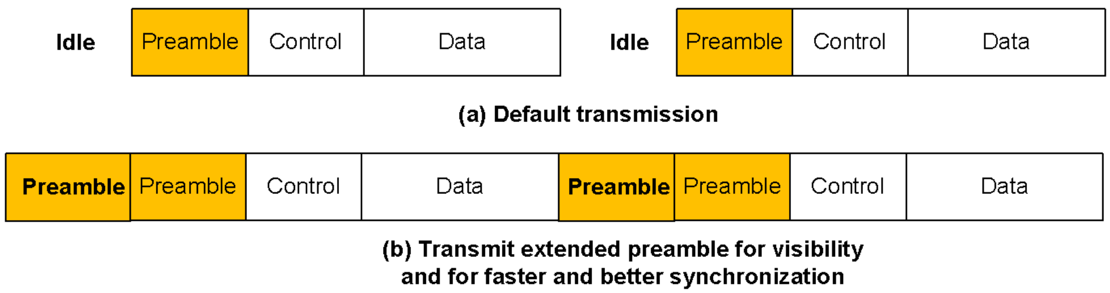


Figure 118—Extended preamble mode provided by the MAC

The MAC uses the knowledge of the idle time in order to figure out how much idle time is present and then increases the number of preamble repetitions during the packet transmission to cover the idle time period. The extended preamble is made continuous to the existing preamble of the next packet transmission. There is a possibility that the idle time may not be an integral multiple of the preamble length. In such cases, it is acceptable to transmit a fraction of the preamble (the latter part) in order to maintain visibility. This fraction of the preamble can be called as a truncated preamble.

The MAC can choose to either transmit a visibility pattern or an extended preamble in the idle mode during regular operation. The choice is indicated to the PHY via the MAC-PHY interface.

Preamble pattern 1010 is shown as an example preamble. Since idle time is not an integral multiple of the preamble, only a fraction of the preamble pattern such as '010' can be sent to complete the idle time.

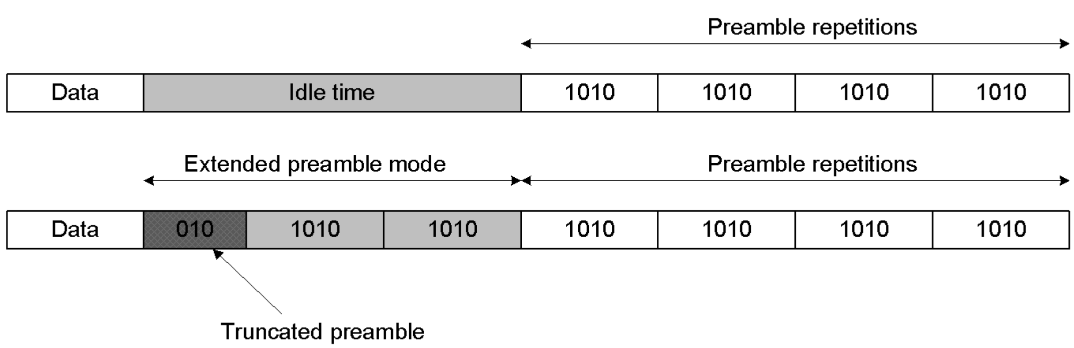


Figure 119—Truncated preamble in extended preamble mode for utilizing idle time for visibility

8.4 Transmitting visibility pattern during uplink for star topology mode

For the star topology mode, since multiple users could be pointing to the infrastructure fixed access point, the point and shoot visibility signal from the mobile device cannot be transmitted continuously. This makes the visibility signal difficult to attain due to the low duty cycle. Hence, the knowledge of idle periods (unused slots) is transmitted by the beacons and the mobile device uses the idle periods (unused slots) for transmitting the visibility pattern to the fixed access point. All mobile devices talking to access point can share the empty slots for the visible frame transmission during uplink.

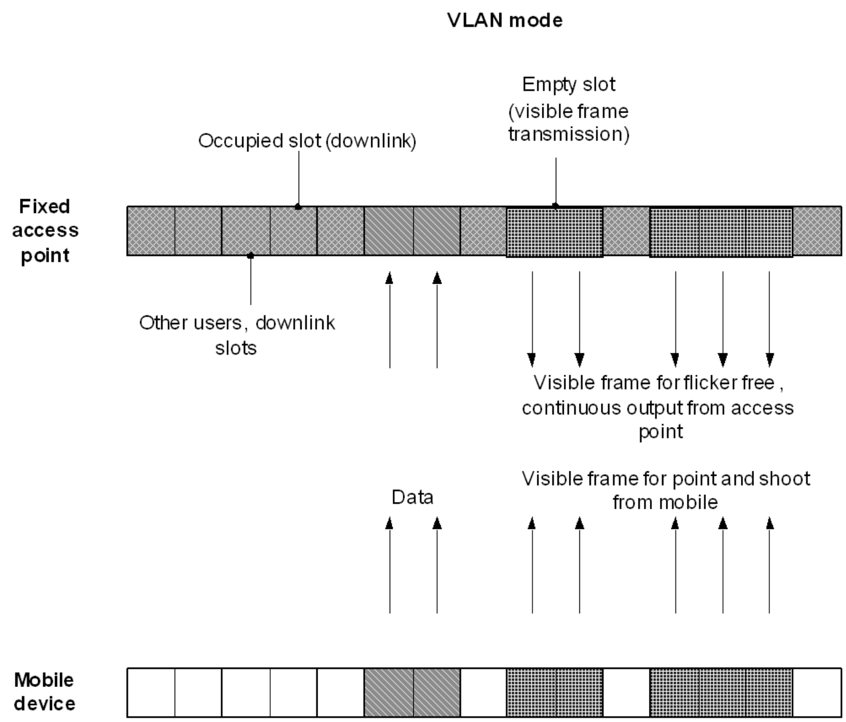


Figure 120—Usage of visible frames during star topology operation

9. Dimming support

The standard does not specify the type of dimming interaction or dimming method. Only items that are dimmer-standards independent are specified. If information (such as the dimming level or dimming type or the fact that dimming is being enabled) from the dimmer is made available, it should be utilized to support dimming. Dimming support is applicable for infrastructure/illumination device class. It is also applicable to vehicles. Due to non-linear human eye response to light, dimming levels as low as 0.1% must be supported (square law phenomenon)

9.1 Dimming override capability

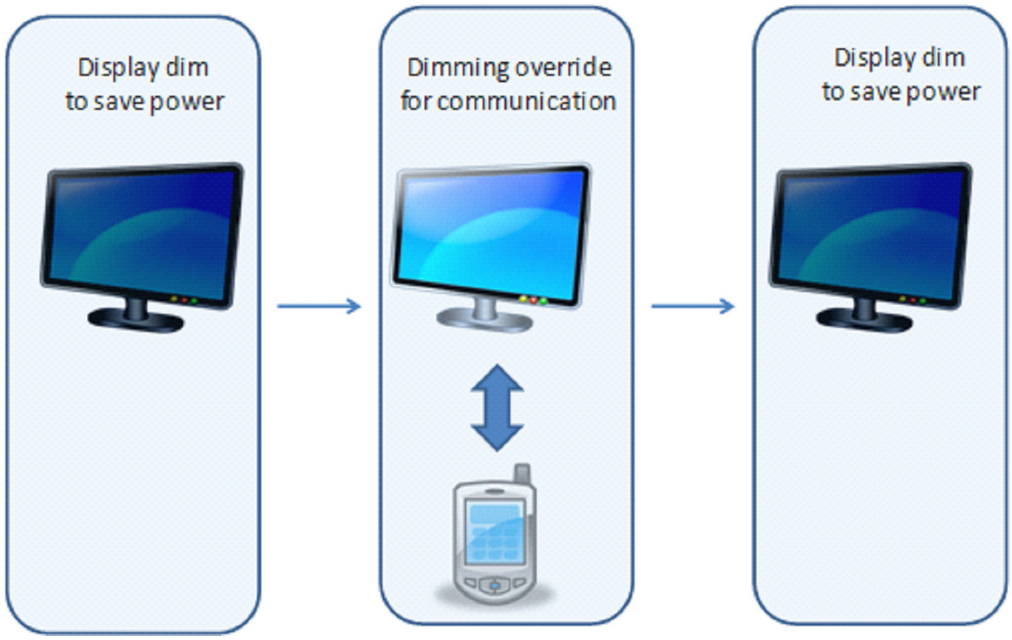


Figure 121—Need for dimming override capability

The standard supports bypassing the dimmer functionality during VLC operation. The dimmer control can be set to maximum brightness to facilitate VLC communication. As soon as the VLC communication is completed, the dimmer regains control of the optical source driver and resumes normal operation.

A dimmer override capability signal is added to the MLME SAP and provided to the external dimmer interface. This dimmer override signal shall be set to '1' by the MAC during VLC operation and shall be set to '0' after the communication has been completed. The usage of this dimmer override signal by the external dimmer circuit is out-of-scope.

9.2 PWM signal override

A PWM signal override capability signal is added to the PLME SAP and provided to the external dimmer interface. This PWM override signal shall be set by the VLC PHY to allow an option where the VLC PHY operation is not affected by the dimmer setting when the dimmer override is not feasible. The duty cycle for the dimmer circuit is then driven by modulation mode provided by the VLC PHY (such as VPM).

9.3 Supporting visibility pattern depending on dimming levels

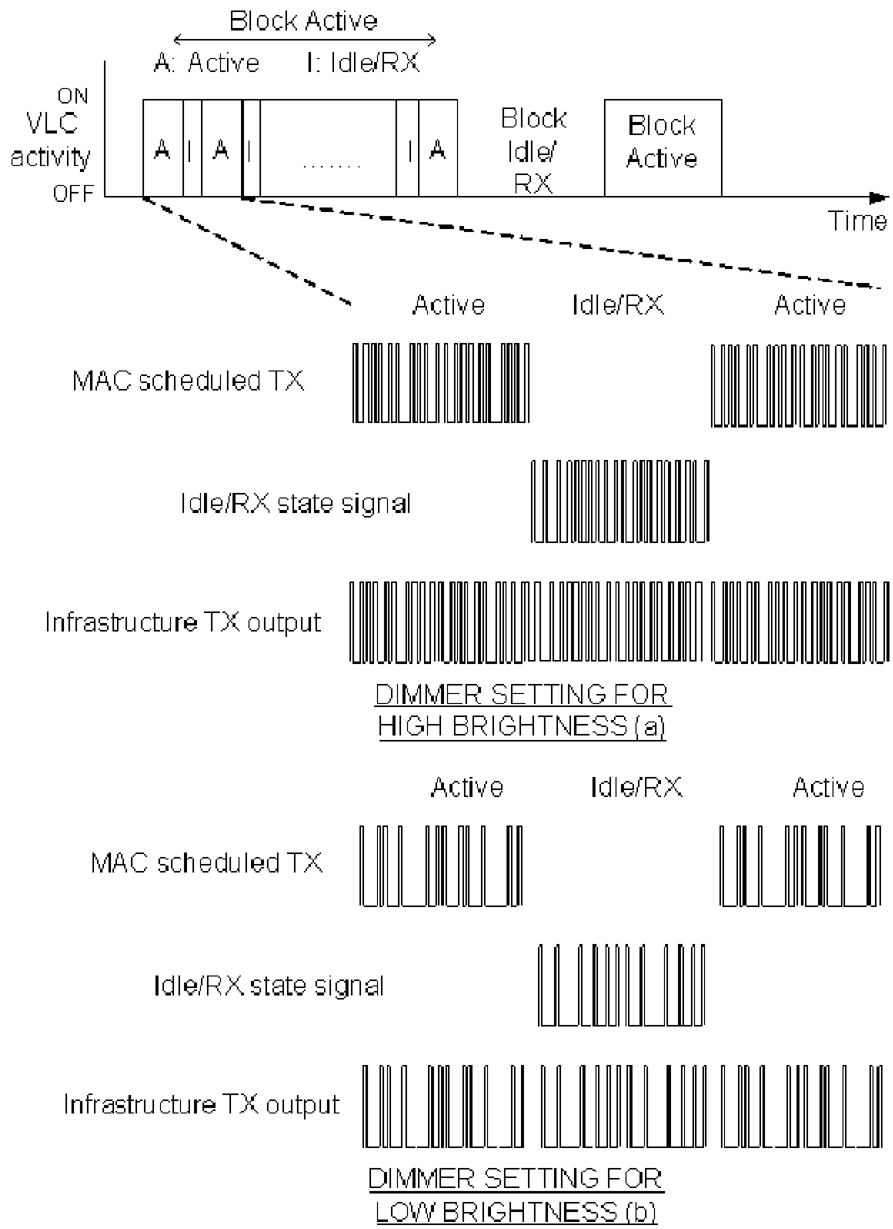
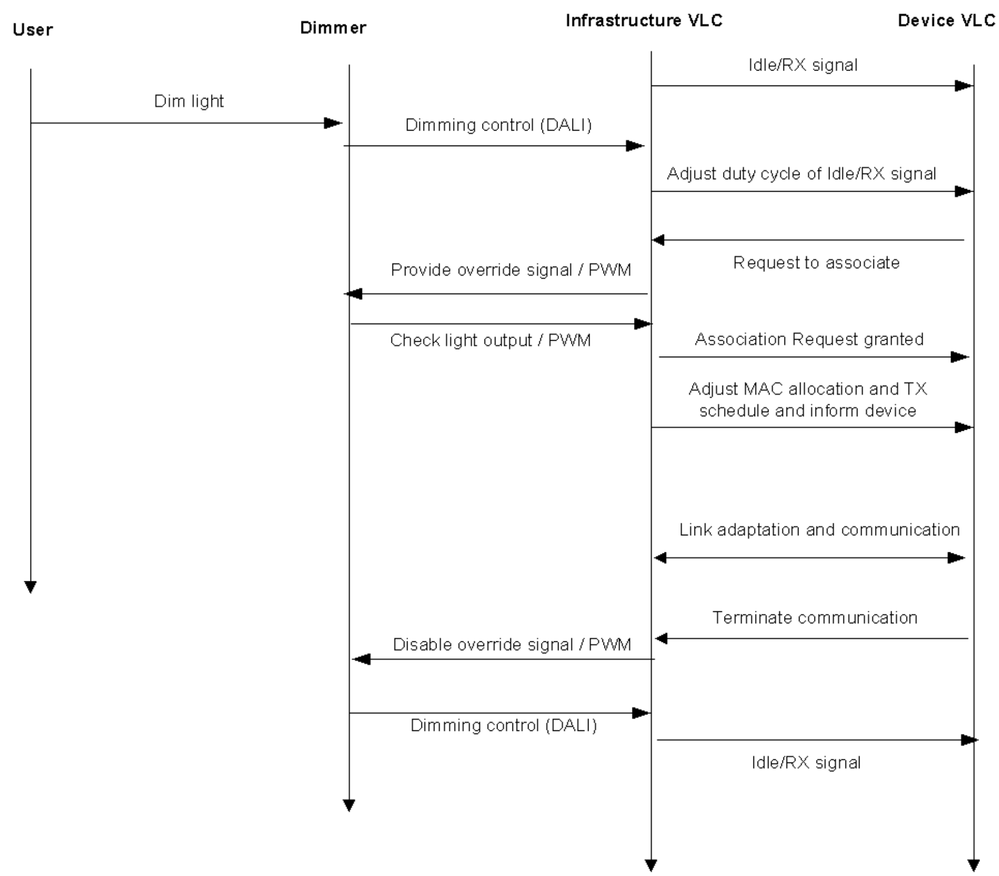


Figure 122—Adapting dimmer pattern and data duty cycle depending on dimmer setting

A visibility (dimming) pattern shall be transmitted during idle/RX state signal to be transmitted during MAC idle or RX states for infrastructure light sources. This is important since we need to maintain visibility and flicker-free operation during idle or RX periods at the infrastructure. The idle/RX signal has the same duty cycle that is used during the active signal so that there is no flicker or visibility effect seen during idle periods. This idle/RX signal and its dependence on the dimmer setting is shown in the figure. The transition of active mode and idle/RX mode can be in large time scale (block active/idle/RX) or in a small time scale (within a communication session). In the large time scale block session activity, when the VLC activity is "ON", there can be small time scaled transition of active mode and idle/RX mode. Dimmer setting (a) illustrates a higher switching frequency for higher brightness, while dimmer setting (b) illustrates a lower switching frequency for lower brightness. The data and the visibility (dimming) pattern shall have the same duty cycle.

9.4 MAC layer transmission adjustment for dimming



We adjust the resource allocation (e.g., TX scheduling) depending on the dimming control and inform the device of these changes. The infrastructure VLC adjusts the resource allocation configurations, (e.g., TX scheduling for single/multiple types of traffic from one VLC device, TX scheduling for multiple VLC devices, power control information, color selection, mobility support (e.g., handover), interference mitigation, etc.) based on the duty cycle requirements from the dimmer. The infrastructure MAC shall ensure that the On/off ratio of transmissions matches the duty cycle requirements set by the dimmer.

9.5 Device discovery and association in the presence of dimming and visibility

The visibility (dimming) pattern can also be used for device discovery when the idle pattern or the data has been modified because of the PHY and MAC layer modulation changes to support dimming. Based on the dimming pattern change and duty cycle, the VLC receiver may choose to select a different infrastructure that is currently not being dimmed or has a higher duty cycle (more illumination).

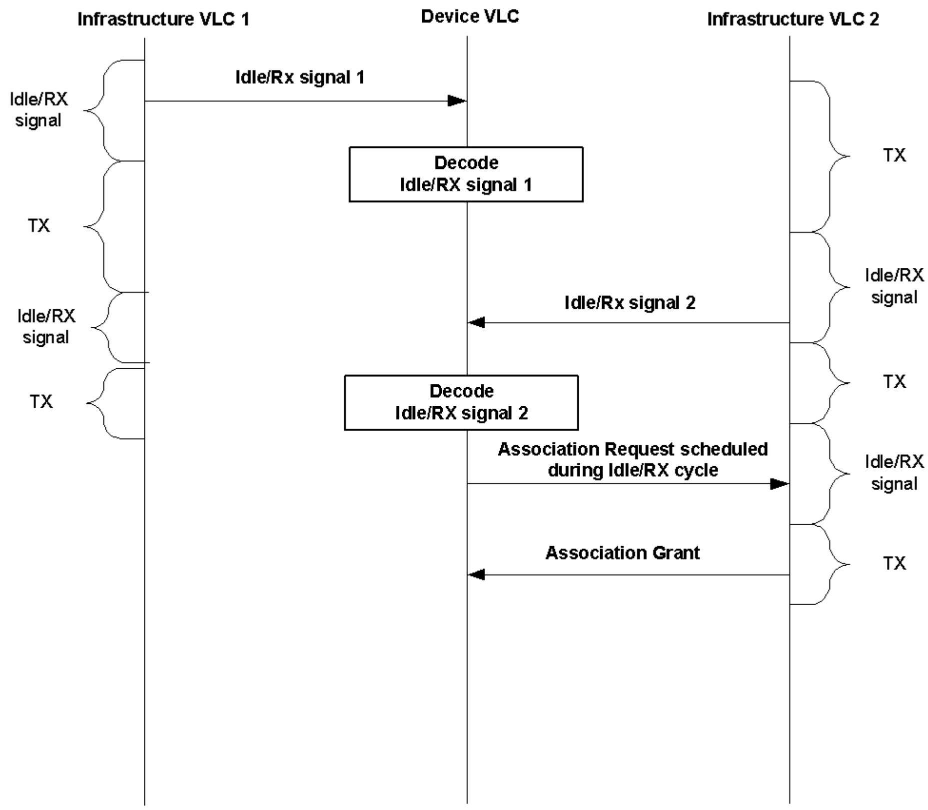


Figure 123—Using dimming pattern as signal to establish link to best infrastructure device

9.6 Link adaptation for dimming support

Dimming cycle patterns of infrastructure should be notified to VLC RX device, so that the VLC receiver could adapt to the dimming pattern. Infrastructure VLC may receive a dimming request from a dimmer triggered by user. A link adaptation timer is used that delays the time between the dimming request and the actual dimming of the light source. With this knowledge of an incoming dimming, the link between the devices can be adapted to work at a new (lower) data rate (if dimmed) without requiring the link to be interrupted or possible link failure. This link adaptation is indicated and supported by the MAC command frame.

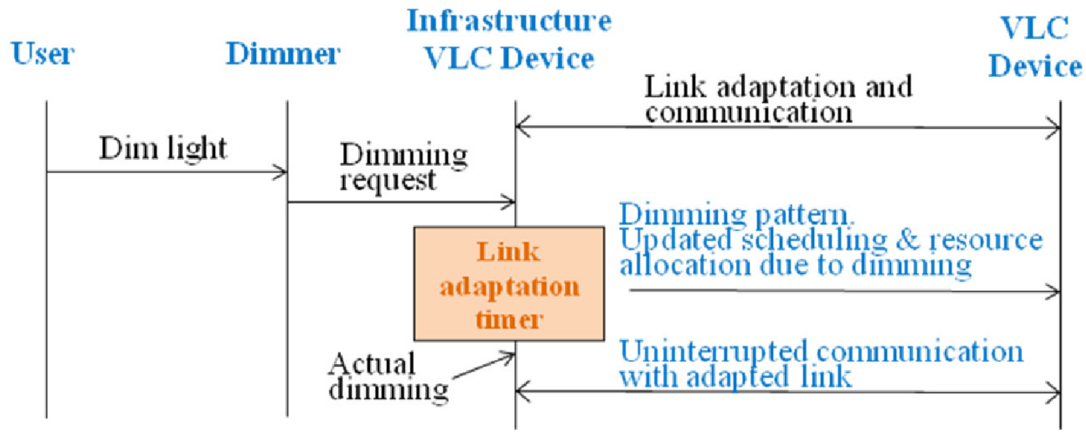


Figure 124—Usage of MAC layer to delay dimming and adapt resources for uninterrupted link

9.7 Maintaining WPANs

This subclause specifies the procedures for identifying WPAN identifier conflicts.

9.7.1 WPAN identifier conflict resolution

In some instances a situation could occur in which two WPANs exist in the same POS with the same WPAN identifier. If this conflict happens, the coordinator and its devices shall perform the WPAN identifier conflict resolution procedure.

This procedure is optional for an RFD.

9.7.1.1 Detection

The PAN coordinator shall conclude that a PAN identifier conflict is present if either of the following apply:

— A beacon frame is received by the PAN coordinator with the PAN Coordinator subfield (see 7.2.2.1.2) set to one and the PAN identifier equal to *macPANId*.

— A PAN ID conflict notification command (see 7.4.5) is received by the PAN coordinator from a device associated with it on its PAN.

A device that is associated through the PAN coordinator (i.e., *macAssociatedPANCoord* is set to TRUE) shall conclude that a PAN identifier conflict is present if the following applies:

— A beacon frame is received by the device with the PAN Coordinator subfield set to one, the PAN identifier equal to *macPANId*, and an address that is equal to neither *macCoordShortAddress* nor *macCoordExtendedAddress*.

A device that is associated through a coordinator that is not the PAN coordinator shall not be capable of detecting a PAN identifier conflict.

9.7.1.2 Resolution

On the detection of a WPAN identifier conflict by a device, it shall generate the WPAN ID conflict notification command (see 7.4.5) and send it to its coordinator. Since the WPAN ID conflict notification command contains an acknowledgment request (see 7.4.3.1), the coordinator shall confirm its receipt by sending an acknowledgment frame. Once the device has received the acknowledgment frame from the coordinator, the MLME shall issue an MLME-SYNC-LOSS.indication primitive with the LossReason parameter set to WPAN_ID_CONFLICT. If the device does not receive an acknowledgment frame, the MLME shall not inform the next higher layer of the WPAN identifier conflict.

On the detection of a WPAN identifier conflict by the coordinator, the MLME shall issue an MLME-SYNC-LOSS.indication to the next higher layer with the LossReason parameter set to WPAN_ID_CONFLICT. The next higher layer of the coordinator may then perform an active scan and, using the information from the scan, select a new WPAN identifier. The algorithm for selecting a suitable WPAN identifier is out of the scope of this standard. If the next higher layer does select a new WPAN identifier, it may then issue an MLME-START.request with the CoordRealignment parameter set to TRUE in order to realign the WPAN, as described in 7.6.2.3.

9.7.1.3 Realigning a WPAN

If a coordinator receives the MLME-START.request primitive (see 7.1.13.1) with the CoordRealignment parameter set to TRUE, the coordinator shall attempt to transmit a coordinator realignment command containing the new parameters for WPANId, LogicalChannel.

When the coordinator is already transmitting beacons and the CoordRealignment parameter is set to TRUE, the next scheduled beacon shall be transmitted on the current channel using the current superframe configuration, with the Frame Pending subfield of the Frame Control field set to one. Immediately following the transmission of the beacon, the coordinator realignment command shall also be transmitted on the current channel using random access.

When the coordinator is not already transmitting beacons and the CoordRealignment parameter is set to TRUE, the coordinator realignment command shall be transmitted immediately on the current channel using random access.

If the transmission of the coordinator realignment command fails due to a channel access failure, the MLME shall notify the next higher layer by issuing the MLME-START.confirm primitive with a status of CHANNEL_ACCESS_FAILURE. The next higher layer may then choose to issue the MLME-START.request primitive again.

Upon successful transmission of the coordinator realignment command, the new superframe configuration and channel parameters shall be put into operation as described in 9.7.1.5 at the subsequent scheduled beacon, or immediately if the coordinator is not already transmitting beacons, and the MAC sublayer shall issue the MLME-START.confirm primitive with a status of SUCCESS.

9.7.1.4 Realignment in a WPAN

If a device has received the coordinator realignment command (see 7.4.8) from the coordinator through which it is associated and the MLME was not carrying out an orphan scan, the MLME shall issue the MLME-SYNC-LOSS.indication primitive with the LossReason parameter set to REALIGNMENT and the WPANId, LogicalChannel, ChannelPage, and the security-related parameters set to the respective fields in the coordinator realignment command. The next higher layer of a coordinator may then issue an MLME-START.request primitive with the CoordRealignment parameter set to TRUE. The next higher layer of a device that is not a coordinator may instead change the superframe configuration or channel parameters through use of the MLME-SET.request primitive.

9.7.1.5 Updating superframe configuration and channel PIB attributes

To update the superframe configuration and channel attributes, the MLME shall assign values from the MLME-START.request primitive parameters to the appropriate PIB attributes. The MLME shall set *macBeaconOrder* to the value of the BeaconOrder parameter. If *macBeaconOrder* is equal to 15, the MLME will also set *macSuperframeOrder* to 15. In this case, this primitive configures a nonbeacon-enabled WPAN. If *macBeaconOrder* is less than 15, the MAC sublayer will set *macSuperframeOrder* to the value of the SuperframeOrder parameter. The MAC sublayer shall also update *macWPANID* with the value of the WPANId parameter and update *phyCurrentChannel* with the values of the LogicalChannel parameters by issuing the PLME-SET.request primitive.

9.7.2 Beacon generation

A device shall be permitted to transmit beacon frames only if *macShortAddress* is not equal to 0xffff.

An FFD shall use the MLME-START.request primitive to begin transmitting beacons only if the BeaconOrder parameter is less than 15. The FFD may begin beacon transmission either as the coordinator of a new WPAN or as a device on a previously established WPAN, depending upon the setting of the WPANCoordinator parameter (see 7.1.13.1). The FFD shall begin beacon transmission on a previously established WPAN only once it has successfully associated with that WPAN.

If the FFD is the coordinator (i.e., the WPANCoordinator parameter is set to TRUE), the MAC sublayer shall ignore the StartTime parameter and begin beacon transmissions immediately. Setting the StartTime parameter to zero shall also cause the MAC sublayer to begin beacon transmissions immediately. If the FFD is not the coordinator and the StartTime parameter is nonzero, the time to begin beacon transmissions shall be calculated using the following method. The StartTime parameter, which is rounded to a backoff slot boundary, shall be added to the time, obtained from the local clock, when the MAC sublayer receives the beacon of the coordinator through which it is associated. The MAC sublayer shall then begin beacon transmissions when the current time, obtained from the local clock, equals the number of calculated symbols. In order for the beacon transmission time to be calculated by the MAC sublayer, the MAC sublayer shall first track the beacon of the coordinator through which it is associated. If the MLME-START.request primitive is issued with a nonzero StartTime parameter and the MAC sublayer is not currently tracking the beacon of its coordinator, the MLME shall not begin beacon transmissions but shall instead issue the MLME-START.confirm primitive with a status of TRACKING_OFF.

If a device misses between one and (*aMaxLostBeacons*–1) consecutive beacon frames from its coordinator, the device shall continue to transmit its own beacons based on both *macBeaconOrder* (see 9.7.1.5) and its local clock. If the device then receives a beacon frame from its coordinator and, therefore, does not lose synchronization, the device shall resume transmitting its own beacons based on the StartTime parameter and the incoming beacon. If a device does lose synchronization with its coordinator, the MLME of the device shall issue the MLME-SYNC-LOSS.indication primitive to the next higher layer and immediately stop transmitting its own beacons. The next higher layer may, at any time following the reception of the MLME-SYNC-LOSS.indication primitive, resume beacon transmissions by issuing a new MLME-START.request primitive.

On receipt of the MLME-START.request primitive, the MAC sublayer shall set the WPAN identifier in *macWPANId* and use this value in the Source WPAN Identifier field of the beacon frame. The address used in the Source Address field of the beacon frame shall contain the value of *aExtendedAddress* if *macShortAddress* is equal to 0xfffe or *macShortAddress* otherwise.

The time of transmission of the most recent beacon shall be recorded in *macBeaconTxTime* and shall be computed so that its value is taken at the same symbol boundary in each beacon frame, the location of which is implementation specific. The symbol boundary, which is specified by the *macSyncSymbolOffset* attribute, is the same as that used in the timestamp of the incoming beacon frame, as described in 9.7.5.1.

All beacon frames shall be transmitted at the beginning of each superframe at an interval equal to *aBaseSuperframeDuration* * 2^n symbols, where *n* is the value of *macBeaconOrder* (the construction of the beacon frame is specified in 7.2.2.1).

Beacon transmissions shall be given priority over all other transmit and receive operations.

9.7.3 Device discovery

The coordinator indicates its presence on a WPAN to other devices by transmitting beacon frames. This allows the other devices to perform device discovery.

A coordinator that is not the coordinator shall begin transmitting beacon frames only when it has successfully associated with a WPAN. The transmission of beacon frames by the device is initiated through the use of the MLME-START.request primitive with the WPANCoordinator parameter set to FALSE. On receipt of this primitive, the MLME shall begin transmitting beacons based on the StartTime parameter (see 9.7.2) using the identifier of the WPAN with which the device has associated, *macWPANId*, and its extended address, *aExtendedAddress*, if *macShortAddress* is equal to 0xfffe, or its short address, *macShortAddress*, otherwise. A beacon frame shall be transmitted at a rate of one beacon frame every *aBaseSuperframeDuration* * 2^n symbols, where *n* is the value of *macBeaconOrder*.

9.7.4 Association and disassociation

This subclause specifies the procedures for association and disassociation.

9.7.4.1 Association

A device shall attempt to associate only after having first performed a MAC sublayer reset, by issuing the MLME-RESET.request primitive with the SetDefaultPIB parameter set to TRUE, and then having completed either an active channel scan (see 7.5.2.1.2) or a passive channel scan (see 7.5.2.1.3). The results of the channel scan would have then been used to choose a suitable WPAN. The algorithm for selecting a suitable WPAN with which to associate from the list of WPAN descriptors returned from the channel scan procedure is out of the scope of this standard.

Following the selection of a WPAN with which to associate, the next higher layers shall request through the MLME-ASSOCIATE.request primitive that the MLME configures the following PHY and MAC PIB attributes to the values necessary for association:

— *phyCurrentChannel* shall be set equal to the LogicalChannel parameter of the MLME-ASSOCIATE.request primitive.
— *macWPANId* shall be set equal to the CoordPANId parameter of the MLME-ASSOCIATE.request primitive.
— *macCoordExtendedAddress* or *macCoordShortAddress*, depending on which is known from the beacon frame from the coordinator through which it wishes to associate, shall be set equal to the CoordAddress parameter of the MLME-ASSOCIATE.request primitive.

A coordinator shall allow association only if *macAssociationPermit* is set to TRUE. Similarly, a device should attempt to associate only with a WPAN through a coordinator that is currently allowing association, as indicated in the results of the scanning procedure. If a coordinator with *macAssociationPermit* set to FALSE receives an association request command from a device, the command shall be ignored.

In order to optimize the association procedure on a beacon-enabled WPAN, a device may begin tracking the beacon of the coordinator through which it wishes to associate a priori. This is achieved by the next higher layer issuing the MLME-SYNC.request primitive with the TrackBeacon parameter set to TRUE.

A device that is instructed to associate with a WPAN, through the MLME-ASSOCIATE.request primitive, shall try to associate only with an existing WPAN and shall not attempt to start its own PAN.

The MAC sublayer of an unassociated device shall initiate the association procedure by sending an association request command (see 7.4.1) to the coordinator of an existing WPAN; if the association request command cannot be sent due to a channel access failure, the MAC sublayer shall notify the next higher layer. Because the association request command contains an acknowledgment request (see 7.4.1.1), the coordinator shall confirm its receipt by sending an acknowledgment frame.

The acknowledgment to an association request command does not mean that the device has associated. The next higher layer of the coordinator needs time to determine whether the current resources available on the VLC WPAN are sufficient to allow another device to associate. The next higher layer should make this decision within *macResponseWaitTime* symbols. If the next higher layer of the coordinator finds that the device was previously associated on its VLC WPAN, all previously obtained device-specific information should be removed. If sufficient resources are available, the next higher layer should allocate a 16-bit short address to the device, and the MAC sublayer shall generate an association response command (see 7.4.2) containing the new address and a status indicating a successful association. If sufficient resources are not available, the next higher layer of the coordinator should inform the MAC sublayer, and the MLME shall generate an association response command containing a status indicating a failure (see Table 68). The association response command shall be sent to the device requesting association using indirect transmission, i.e., the association response command frame shall be added to the list of pending transactions stored on the coordinator and extracted at the discretion of the device concerned using the method described in 9.7.7.3.

If the Allocate Address subfield of the Capability Information field (see 7.4.1.2) of the association request command is set to one, the next higher layer of the coordinator shall allocate a 16-bit address with a range depending on the addressing mode supported by the coordinator, as described in Table 77. If the Allocate Address subfield of the association request command is set to zero, the 16-bit short address shall be equal to 0xfffe. A short address of 0xfffe is a special case that indicates that the device has associated, but has not been allocated a short address by the coordinator. In this case, the device shall use only its 64-bit extended address to operate on the network.

On receipt of the acknowledgment to the association request command, the device shall wait for at most *macResponseWaitTime* symbols for the coordinator to make its association decision; the PIB attribute *macResponseWaitTime* is a network-topology-dependent parameter and may be set to match the specific requirements of the network that a device is trying to join. If the device is tracking the beacon, it shall attempt to extract the association response command from the coordinator whenever it is indicated in the beacon frame. If the device is not tracking the beacon, it shall attempt to extract the association response command from the coordinator after *macResponseWaitTime* symbols. If the device does not extract an association response command frame from the coordinator within *macResponseWaitTime* symbols, the MLME shall issue the MLME-ASSOCIATE.confirm primitive with a status of NO_DATA, and the association attempt shall be deemed a failure. In this case, the next higher layer shall terminate any tracking of the beacon. This is achieved by issuing the MLME-SYNC.request primitive with the TrackBeacon parameter set to FALSE.

Because the association response command contains an acknowledgment request (see 7.4.2.1), the device requesting association shall confirm its receipt by sending an acknowledgment frame. If the Association Status field of the command indicates that the association was successful, the device shall store the address contained in the 16-bit Short Address field of the command in *macShortAddress*; communication on the VLC WPAN using this short address shall depend on its range, as described in Table 77. If the original beacon selected for association following a scan contained the short address of the coordinator, the extended address of the coordinator, contained in the MHR of the association response command frame, shall be stored in *macCoordExtendedAddress*.

Table 77—Usage of the 16-bit short address

Value of *macShortAddress*	Description
0x0000–0xfffd	If a source address is included, the device shall use short source addressing mode for beacon and data frames and the appropriate source addressing mode specified in 7.4 for MAC command frames.
0xfffe	If a source address is included, the device shall use extended source addressing mode for beacon and data frames and the appropriate source addressing mode specified in 7.4 for MAC command frames.
0xffff	The device is not associated and, therefore, shall not perform any data frame communication. The device shall use the appropriate source addressing mode specified in 7.4 for MAC command frames.

If the Association Status field of the command indicates that the association was unsuccessful, the device shall set *macWPANId* to the default value (0xffff).

9.7.4.2 Disassociation

The disassociation procedure is initiated by the next higher layer by issuing the MLME-DISASSOCIATE.request primitive to the MLME.

When a coordinator wants one of its associated devices to leave the VLC WPAN, the MLME of the coordinator shall send the disassociation notification command in the manner specified by the TxIndirect parameter of the MLME-DISASSOCIATE.request primitive previously sent by the next higher layer. If TxIndirect is TRUE, the MLME of the coordinator shall send the disassociation notification command to the device using indirect transmission, i.e., the disassociation notification command frame shall be added to the list of pending transactions stored on the coordinator and extracted at the discretion of the device concerned using the method described in 9.7.7.3. If the command frame is not successfully extracted by the device, the coordinator should consider the device disassociated. Otherwise, the MLME shall send the disassociation notification command to the device directly. In this case, if the disassociation notification command cannot be sent due to a channel access failure, the MAC sublayer shall notify the next higher layer.

Because the disassociation command contains an acknowledgment request (see 7.4.3.1), the receiving device shall confirm its receipt by sending an acknowledgment frame. If the direct or indirect transmission fails, the coordinator should consider the device disassociated.

If an associated device wants to leave the VLC WPAN, the MLME of the device shall send a disassociation notification command to its coordinator. If the disassociation notification command cannot be sent due to a channel access failure, the MAC sublayer shall notify the next higher layer. Because the disassociation command contains an acknowledgment request (see 7.4.3.1), the coordinator shall confirm its receipt by sending an acknowledgment frame. However, even if the acknowledgment is not received, the device should consider itself disassociated.

If the source address contained in the disassociation notification command is equal to *macCoord-ExtendedAddress*, the device should consider itself disassociated. If the command is received by a coordinator and the source is not equal to *macCoordExtendedAddress*, it shall verify that the source address corresponds to one of its associated devices; if so, the coordinator should consider the device disassociated. If none of the above conditions is satisfied, the command shall be ignored.

An associated device shall disassociate itself by removing all references to the VLC WPAN; the MLME shall set *macWPANId*, *macShortAddress*, *macAssociatedWPANCoord*, *macCoordShortAddress* and *macCoordExtended-Address* to the default values. The next higher layer of a coordinator should disassociate a device by removing all references to that device.

The next higher layer of the requesting device shall be notified of the result of the disassociation procedure through the MLME-DISASSOCIATE.confirm primitive.

9.7.5 Synchronization

This subclause specifies the procedures for coordinators to generate beacon frames and for devices to synchronize with a coordinator. For WPANs supporting beacons, synchronization is performed by receiving and decoding the beacon frames. For WPANs not supporting beacons, synchronization is performed by polling the coordinator for data.

9.7.5.1 Synchronization with beacons

All devices operating on a beacon-enabled VLC WPAN (i.e., *macBeaconOrder* < 15) shall be able to acquire beacon sychronization in order to detect any pending messages or to track the beacon. Devices shall be permitted to acquire beacon synchronization only with beacons containing the VLC WPAN identifier specified in *macWPANId*. If *macWPANId* specifies the broadcast WPAN identifier (0xffff), a device shall not attempt to acquire beacon synchronization.

A device is instructed to attempt to acquire the beacon through the MLME-SYNC.request primitive. If tracking is specified in the MLME-SYNC.request primitive, the device shall attempt to acquire the beacon and keep track of it by regular and timely activation of its receiver. If tracking is not specified, the device shall either attempt to acquire the beacon only once or terminate the tracking after the next beacon if tracking was enabled through a previous request.

To acquire beacon synchronization, a device shall enable its receiver and search for at most [*aBaseSuperframeDuration* * (2^n + 1)] symbols, where *n* is the value of *macBeaconOrder*. If a beacon frame containing the current WPAN identifier of the device is not received, the MLME shall repeat this search. Once the number of missed beacons reaches *aMaxLostBeacons*, the MLME shall notify the next higher layer by issuing the MLME-SYNC-LOSS.indication primitive with a loss reason of BEACON_LOSS.

The MLME shall timestamp each received beacon frame at the same symbol boundary within each frame, the location of which is described by the *macSyncSymbolOffset* attribute. The symbol boundary shall be the same as that used in the timestamp of the outgoing beacon frame, stored in *macBeaconTxTime*. The timestamp value shall be that of the local clock of the device at the time of the symbol boundary. The timestamp is intended to be a relative time measurement that may or may not be made absolute, at the discretion of the implementer.

If a protected beacon frame is received (i.e., the Security Enabled subfield in the Frame Control field is set to one), the device shall attempt to unsecure the beacon frame using the unsecuring process described in 9.7.9.2.3.

If the status from the unsecuring process is not SUCCESS, the MLME shall issue an MLME-COMM-STATUS.indication primitive with the status parameter set to the status from the unsecuring process, indicating the error.

The security-related elements of the WPAN descriptor corresponding to the beacon (see Table 41) shall be set to the corresponding parameters returned by the unsecuring process. The SecurityFailure element of the WPAN descriptor shall be set to SUCCESS if the status from the unsecuring process is SUCCESS and set to one of the other status codes indicating an error in the security processing otherwise.

If a beacon frame is received, the MLME shall discard the beacon frame if the Source Address and the Source WPAN Identifier fields of the MHR of the beacon frame do not match the coordinator source address (*macCoordShortAddress* or *macCoordExtendedAddress*, depending on the addressing mode) and the identifier of the device (*macWPANId*).

If a valid beacon frame is received and *macAutoRequest* is set to FALSE, the MLME shall indicate the beacon parameters to the next higher layer by issuing the MLME-BEACON-NOTIFY.indication primitive. If a beacon frame is received and *macAutoRequest* is set to TRUE, the MLME shall first issue the MLME-BEACON-NOTIFY.indication primitive if the beacon contains any payload. The MLME shall then compare its address with those addresses in the Address List field of the beacon frame. If the Address List field contains the 16-bit short or 64-bit extended address of the device and the source WPAN identifier matches *macWPANId*, the MLME shall follow the procedure for extracting pending data from the coordinator (see 9.7.7.3).

If beacon tracking is activated, the MLME shall enable its receiver at a time prior to the next expected beacon frame transmission, i.e., just before the known start of the next superframe. If the number of consecutive beacons missed by the MLME reaches *aMaxLostBeacons*, the MLME shall respond with the MLME-SYNC-LOSS.indication primitive with a loss reason of BEACON_LOST.

9.7.5.2 Synchronization without beacons

All devices operating on a nonbeacon-enabled WPAN (*macBeaconOrder* = 15) shall be able to poll the coordinator for data at the discretion of the next higher layer.

A device is instructed to poll the coordinator when the MLME receives the MLME-POLL.request primitive. On receipt of this primitive, the MLME shall follow the procedure for extracting pending data from the coordinator (see 9.7.7.3).

9.7.5.3 Orphaned device realignment

If the next higher layer receives repeated communications failures following its requests to transmit data, it may conclude that it has been orphaned. A single communications failure occurs when a device transaction fails to reach the coordinator, i.e., an acknowledgment is not received after *macMaxFrameRetries* attempts at sending the data. If the next higher layer concludes that it has been orphaned, it may instruct the MLME to either perform the orphaned device realignment procedure, or to reset the MAC sublayer and then perform the association procedure.

If the decision has been made by the next higher layer to perform the orphaned device realignment procedure, it will have issued an MLME-SCAN.request with the ScanType parameter set to orphan scan and the ScanChannel parameter containing the list of channels to be scanned. Upon receiving this primitive, the MAC sublayer shall begin an orphan scan, as described in 7.5.2.1.4.

If the orphan scan is successful (i.e., its WPAN has been located), the device shall update its MAC PIB with the WPAN information contained in the coordinator realignment command (see 7.4.8).

9.7.6 Transaction handling

Transactions can be instigated from the devices themselves rather than from the coordinator. In other words, either the coordinator needs to indicate in its beacon when messages are pending for devices or the devices themselves need to poll the coordinator to determine whether they have any messages pending. Such transfers are called indirect transmissions.

The coordinator shall begin handling a transaction on receipt of an indirect transmission request either via the MCPS-DATA.request primitive or via a request from the MLME to send a MAC command instigated by a primitive from the next higher layer, such as the MLME-ASSOCIATE.response primitive (see 7.1.3.3). On completion of the transaction, the MAC sublayer shall indicate a status value to the next higher layer. If a request primitive instigated the indirect transmission, the corresponding confirm primitive shall be used to convey the appropriate status value. Conversely, if a response primitive instigated the indirect transmission, the MLME-COMM-STATUS.indication primitive shall be used to convey the appropriate status value. The

MLME-COMM-STATUS.indication primitive can be related to its corresponding response primitive by examining the Destination Address field.

The information contained in the indirect transmission request forms a transaction, and the coordinator shall be capable of storing at least one transaction. On receipt of an indirect transmission request, if there is no capacity to store another transaction, the MAC sublayer shall indicate to the next higher layer a status of TRANSACTION_OVERFLOW in the appropriate corresponding primitive.

If the coordinator is capable of storing more than one transaction, it shall ensure that all the transactions for the same device are sent in the order in which they arrived at the MAC sublayer. For each transaction sent, if another exists for the same device, the MAC sublayer shall set its Frame Pending subfield to one, indicating the additional pending data.

Each transaction shall persist in the coordinator for at most *macTransactionPersistenceTime*. If the transaction is not successfully extracted by the appropriate device within this time, the transaction information shall be discarded and the MAC sublayer shall indicate to the next higher layer a status of TRANSACTION_EXPIRED in the appropriate corresponding primitive. In order to be successfully extracted, an acknowledgment shall be received if one was requested.

If the transaction was successful, the transaction information shall be discarded, and the MAC sublayer shall indicate to the next higher layer a status of SUCCESS in the appropriate corresponding primitive.

If the coordinator transmits beacons, it shall list the addresses of the devices to which each transaction is associated in the Address List field and indicate the number of addresses in the Pending Address Specification field of the beacon frame. If the coordinator is able to store more than seven pending transactions, it shall indicate them in its beacon on a first-come-first-served basis, ensuring that the beacon frame contains at most seven addresses. For transactions requiring a GTS, the coordinator shall not add the address of the recipient to its list of pending addresses in the beacon frame. Instead it shall transmit the transaction in the GTS allocated for the device (see 9.7.8.3).

On a beacon-enabled VLC WPAN, if there is a transaction pending for the broadcast address, the Frame Pending subfield of the Frame Control field in the beacon frame shall be set to one, and the pending message shall be transmitted immediately following the beacon using the random access algorithm. If there is a second message pending for the broadcast address, its transmission shall be delayed until the following superframe. Only one broadcast message shall be allowed to be sent indirectly per superframe.

On a beacon-enabled VLC WPAN, a device that receives a beacon containing its address in the list of pending addresses shall attempt to extract the data from the coordinator. On a nonbeacon-enabled VLC WPAN, a device shall attempt to extract the data from the coordinator on receipt of the MLME-POLL.request primitive. The procedure for extracting pending data from the coordinator is described in 9.7.7.3. If a device receives a beacon with the Frame Pending subfield set to one, it shall leave its receiver enabled for up to *macMaxFrameTotalWaitTime* symbols to receive the broadcast data frame from the coordinator.

9.7.7 Transmission, reception, and acknowledgment

This subclause describes the fundamental procedures for transmission, reception, and acknowledgment.

9.7.7.1 Transmission

Each device shall store its current DSN value in the MAC PIB attribute *macDSN* and initialize it to a random value; the algorithm for choosing a random number is out of the scope of this standard. Each time a data or a MAC command frame is generated, the MAC sublayer shall copy the value of *macDSN* into the Sequence Number field of the MHR of the outgoing frame and then increment it by one. Each device shall generate exactly one DSN regardless of the number of unique devices with which it wishes to communicate. The value of *macDSN* shall be permitted to roll over.

Each coordinator shall store its current BSN value in the MAC PIB attribute *macBSN* and initialize it to a random value; the algorithm for choosing a random number is out of the scope of this standard. Each time a beacon frame is generated, the MAC sublayer shall copy the value of *macBSN* into the Sequence Number field of the MHR of the outgoing frame and then increment it by one. The value of *macBSN* shall be permitted to roll over.

It should be noted that both the DSN and BSN are 8-bit values and, therefore, have limited use to the next higher layer (e.g., in the case of the DSN, in detecting retransmitted frames).

The Source Address field, if present, shall contain the address of the device sending the frame. When a device has associated and has been allocated a 16-bit short address (i.e., *macShortAddress* is not equal to 0xfffe or 0xffff), it shall use that address in preference to its 64-bit extended address (i.e., *aExtendedAddress*) wherever possible. When a device has not yet associated to a WPAN or *macShortAddress* is equal to 0xffff, it shall use its 64-bit extended address in all communications requiring the Source Address field. If the Source Address field is not present, the originator of the frame shall be assumed to be the coordinator, and the Destination Address field shall contain the address of the recipient.

The Destination Address field, if present, shall contain the address of the intended recipient of the frame, which may be either a 16-bit short address or a 64-bit extended address. If the Destination Address field is not present, the recipient of the frame shall be assumed to be the coordinator, and the Source Address field shall contain the address of the originator.

If both destination and source addressing information is present, the MAC sublayer shall compare the destination and source WPAN identifiers. If the WPAN identifiers are identical, the WPAN ID Compression subfield of the Frame Control field shall be set to one, and the source WPAN identifier shall be omitted from the transmitted frame. If the WPAN identifiers are different, the WPAN ID Compression subfield of the Frame Control field shall be set to zero, and both Destination WPAN Identifier and Source WPAN Identifier fields shall be included in the transmitted frame. If only either the destination or the source addressing information is present, the WPAN ID Compression subfield of the Frame Control field shall be set to zero, and the WPAN identifier field of the single address shall be included in the transmitted frame.

If the frame is to be transmitted on a beacon-enabled PAN, the transmitting device shall attempt to find the beacon before transmitting. If the beacon is not being tracked (see 9.7.5.1) and hence the device does not know where the beacon will appear, it shall enable its receiver and search for at most [*aBaseSuperframeDuration* * (2^n + 1)] symbols, where n is the value of *macBeaconOrder,* in order to find the beacon. If the beacon is not found after this time, the device shall transmit the frame following the successful application of the unslotted version of the random access algorithm (see 7.7.3.3). Once the beacon has been found, either after a search or due to its being tracked, the frame shall be transmitted in the appropriate portion of the superframe. Transmissions in the CAP shall follow a successful application of the slotted version of the random access algorithm (see 7.7.3.3), and transmissions in a GTS shall not use random access.

If the frame is to be transmitted on a nonbeacon-enabled VLC WPAN, the frame shall be transmitted following the successful application of the unslotted version of the random access algorithm (see 7.7.3.3).

For either a beacon-enabled VLC WPAN or a nonbeacon-enabled VLC WPAN, if the transmission is direct and originates due to a primitive issued by the next higher layer and the random access algorithm fails, the next higher layer shall be notified. If the transmission is indirect and the random access algorithm fails, the frame shall remain in the transaction queue until it is requested again and successfully transmitted or until the transaction expires.

The device shall process the frame using the outgoing frame security procedure described in 9.7.9.2.1.

If the status from the outgoing frame security procedure is not SUCCESS, the MLME shall issue the corresponding confirm or MLME-COMM-STATUS.indication primitive with the status parameter set to the status from the outgoing frame security procedure, indicating the error.

To transmit the frame, the MAC sublayer shall first enable the transmitter by issuing the PLME-SET-TRX-STATE.request primitive with a state of TX_ON to the PHY. On receipt of the PLME-SET-TRX-STATE.confirm primitive with a status of either SUCCESS or TX_ON, the constructed frame shall then be transmitted by issuing the PD-DATA.request primitive. Finally, on receipt of the PD-DATA.confirm primitive, the MAC sublayer shall disable the transmitter by issuing the PLME-SET-TRX-STATE.request primitive with a state of RX_ON or TRX_OFF to the PHY, depending on whether the receiver is to be enabled following the transmission. In the case where the Acknowledgment Request subfield of the Frame Control field is set to one, the MAC sublayer shall enable the receiver immediately following the transmission of the frame by issuing the PLME-SET-TRX-STATE.request primitive with a state of RX_ON to the PHY.

9.7.7.2 Reception and rejection

Each device may choose whether the MAC sublayer is to enable its receiver during idle periods. During these idle periods, the MAC sublayer shall still service transceiver task requests from the next higher layer. A transceiver task shall be defined as a transmission request with acknowledgment reception, if required, or a reception request. On completion of each transceiver task, the MAC sublayer shall request that the PHY enables or disables its receiver, depending on the values of *macBeaconOrder* and *macRxOnWhenIdle.* If *macBeaconOrder* is less than 15, the value of *macRxOnWhenIdle* shall be considered relevant only during idle periods of the CAP of the incoming superframe. If *macBeaconOrder* is equal to 15, the value of *macRxOnWhenIdle* shall be considered relevant at all times.

Due to the nature of radio communications, a device with its receiver enabled will be able to receive and decode transmissions from all devices complying with this standard that are currently operating on the same channel and are in its POS, along with interference from other sources. The MAC sublayer shall, therefore, be able to filter incoming frames and present only the frames that are of interest to the upper layers.

For the first level of filtering, the MAC sublayer shall discard all received frames that do not contain a correct value in their FCS field in the MFR (see 7.2.1.9). The FCS field shall be verified on reception by recalculating the purported FCS over the MHR and MAC payload of the received frame and by subsequently comparing this value with the received FCS field. The FCS field of the received frame shall be considered to be correct if these values are the same and incorrect otherwise.

The second level of filtering shall be dependent on whether the MAC sublayer is currently operating in promiscuous mode. In promiscuous mode, the MAC sublayer shall pass all frames received after the first filter directly to the upper layers without applying any more filtering or processing. The MAC sublayer shall be in promiscuous mode if *macPromiscuousMode* is set to TRUE.

If the MAC sublayer is not in promiscuous mode (i.e., *macPromiscuousMode* is set to FALSE), it shall accept only frames that satisfy all of the following third-level filtering requirements:

- The Frame Type subfield shall not contain a reserved frame type.
- The Frame Version subfield shall not contain a reserved value.
- If a destination WPAN identifier is included in the frame, it shall match *macWPANId* or shall be the broadcast WPAN identifier (0xffff).
- If a short destination address is included in the frame, it shall match either *macShortAddress* or the broadcast address (0xffff). Otherwise, if an extended destination address is included in the frame, it shall match *aExtendedAddress*.

— If the frame type indicates that the frame is a beacon frame, the source WPAN identifier shall match *macWPANId* unless *macWPANId* is equal to 0xffff, in which case the beacon frame shall be accepted regardless of the source WPAN identifier.
— If only source addressing fields are included in a data or MAC command frame, the frame shall be accepted only if the device is the coordinator and the source WPAN identifier matches *macWPANId*.

If any of the third-level filtering requirements are not satisfied, the MAC sublayer shall discard the incoming frame without processing it further. If all of the third-level filtering requirements are satisfied, the frame shall be considered valid and processed further. For valid frames that are not broadcast, if the Frame Type subfield indicates a data or MAC command frame and the Acknowledgment Request subfield of the Frame Control field is set to one, the MAC sublayer shall send an acknowledgment frame. Prior to the transmission of the acknowledgment frame, the sequence number included in the received data or MAC command frame shall be copied into the Sequence Number field of the acknowledgment frame. This step will allow the transaction originator to know that it has received the appropriate acknowledgment frame.

If the WPAN ID Compression subfield of the Frame Control field is set to one and both destination and source addressing information is included in the frame, the MAC sublayer shall assume that the omitted Source WPAN Identifier field is identical to the Destination WPAN Identifier field.

The device shall process the frame using the incoming frame security procedure described in 9.7.9.2.3.

If the status from the incoming frame security procedure is not SUCCESS, the MLME shall issue the corresponding confirm or MLME-COMM-STATUS.indication primitive with the status parameter set to the status from the incoming frame security procedure, indicating the error, and with the security-related parameters set to the corresponding parameters returned by the unsecuring process.

If the valid frame is a data frame, the MAC sublayer shall pass the frame to the next higher layer. This is achieved by issuing the MCPS-DATA.indication primitive containing the frame information. The security-related parameters of the MCPS-DATA.indication primitive shall be set to the corresponding parameters returned by the unsecuring process.

If the valid frame is a MAC command or beacon frame, it shall be processed by the MAC sublayer accordingly, and a corresponding confirm or indication primitive may be sent to the next higher layer. The security-related parameters of the corresponding confirm or indication primitive shall be set to the corresponding parameters returned by the unsecuring process.

9.7.7.3 Extracting pending data from a coordinator

A device on a beacon-enabled VLC WPAN can determine whether any frames are pending for it by examining the contents of the received beacon frame, as described in 9.7.5.1. If the address of the device is contained in the Address List field of the beacon frame and *macAutoRequest* is TRUE, the MLME of the device shall send a data request command (see 7.4.4) to the coordinator during the CAP with the Acknowledgment Request subfield of the Frame Control field set to one; the only exception to this is if the beacon frame is received while performing an active or passive scan (see 9.7.1). There are two other cases for which the MLME shall send a data request command to the coordinator. The first case is when the MLME receives the MLME-POLL.request primitive. In the second case, a device may send a data request command *macResponseWaitTime* symbols after the acknowledgment to a request command frame, such as during the association procedure. If the data request is intended for the coordinator, the destination address information may be omitted.

If the data request command originated from an MLME-POLL.request primitive, the MLME shall perform the security process on the data request command based on the SecurityLevel, KeyIdMode, KeySource, and KeyIndex parameters of the MLME-POLL.request primitive, according to 9.7.9.2.1. Otherwise, the MLME shall perform the security process on the data request command based on the *macAutoRequestSecurityLevel*, *macAutoRequestKeyIdMode*, *macAutoRequestKeySource,* and *macAutoRequestKeyIndex* PIB attributes, according to 9.7.9.2.1.

On successfully receiving a data request command, the coordinator shall send an acknowledgment frame, thus confirming its receipt. If the coordinator has enough time to determine whether the device has a frame pending before sending the acknowledgment frame (see 9.7.7.4.2), it shall set the Frame Pending subfield of the Frame Control field of the acknowledgment frame accordingly to indicate whether a frame is actually pending for the device. If this is not possible, the coordinator shall set the Frame Pending subfield of the acknowledgment frame to one.

On receipt of the acknowledgment frame with the Frame Pending subfield set to zero, the device shall conclude that there are no data pending at the coordinator.

On receipt of the acknowledgment frame with the Frame Pending subfield set to one, a device shall enable its receiver for at most *macMaxFrameTotalWaitTime* CAP symbols in a beacon-enabled VLC WPAN, or symbols in a nonbeacon-enabled VLC WPAN, to receive the corresponding data frame from the coordinator. If there is an actual data frame pending within the coordinator for the requesting device, the coordinator shall send the frame to the device using one of the mechanisms described in this subclause. If there is no data frame pending for the requesting device, the coordinator shall send a data frame without requesting acknowledgment to the device containing a zero length payload, indicating that no data are present, using one of the mechanisms described in this subclause.

The data frame following the acknowledgment of the data request command shall be transmitted using one of the following mechanisms:

- Without using random access, if the MAC sublayer can commence transmission of the data frame between *aTurnaroundTime* and (*aTurnaroundTime* + *aUnitBackoffPeriod*) symbols, on a backoff slot boundary, and there is time remaining in the CAP for the message, appropriate IFS, and acknowledgment (see 6.4.1 for an explanation of *aTurnAroundTime*). If a requested acknowledgment frame is not received following this data frame, the process shall begin anew following the receipt of a new data request command.
- Using random access, otherwise.

If the requesting device does not receive a data frame from the coordinator within *macMaxFrameTotalWaitTime* CAP symbols in a beacon-enabled VLC WPAN, or symbols in a nonbeacon-enabled VLC WPAN, or if the requesting device receives a data frame from the coordinator with a zero length payload, it shall conclude that there are no data pending at the coordinator. If the requesting device does receive a data frame from the coordinator, it shall send an acknowledgment frame, if requested, thus confirming receipt.

If the Frame Pending subfield of the Frame Control field of the data frame received from the coordinator is set to one, the device still has more data pending with the coordinator. In this case it may extract the data by sending a new data request command to the coordinator.

9.7.7.4 Use of acknowledgments and retransmissions

A data or MAC command frame shall be sent with the Acknowledgment Request subfield of its Frame Control field set appropriately for the frame. A beacon or acknowledgment frame shall always be sent with the Acknowledgment Request subfield set to zero. Similarly, any frame that is broadcast shall be sent with its Acknowledgment Request subfield set to zero.

9.7.7.4.1 No acknowledgment

A frame transmitted with its Acknowledgment Request subfield set to zero shall not be acknowledged by its intended recipient. The originating device shall assume that the transmission of the frame was successful.

The message sequence chart in Figure 125 shows the scenario for transmitting a single frame of data from an originator to a recipient without requiring an acknowledgment. In this case, the originator transmits the data frame with the Acknowledgment Request (AR) subfield of the Frame Control field equal to zero.

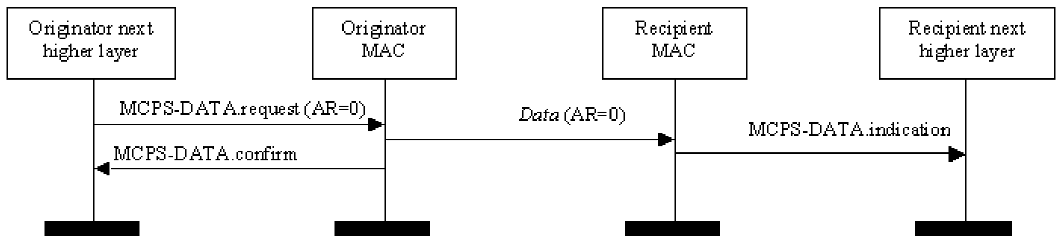


Figure 125—Successful data transmission without an acknowledgment

9.7.7.4.2 Acknowledgment

A frame transmitted with the Acknowledgment Request subfield of its Frame Control field set to one shall be acknowledged by the recipient. If the intended recipient correctly receives the frame, it shall generate and send an acknowledgment frame containing the same DSN from the data or MAC command frame that is being acknowledged.

The transmission of an acknowledgment frame in a nonbeacon-enabled VLC WPAN or in the CFP shall commence *aTurnaroundTime* symbols after the reception of the last symbol of the data or MAC command frame. The transmission of an acknowledgment frame in the CAP shall commence either *aTurnaroundTime* symbols after the reception of the last symbol of the data or MAC command frame or at a backoff slot boundary. In the latter case, the transmission of an acknowledgment frame shall commence between *aTurnaroundTime* and (*aTurnaroundTime* + *aUnitBackoffPeriod*) symbols after the reception of the last symbol of the data or MAC command frame. The constant *aTurnaroundTime* is defined in Table 30 (see 6.4.1).

The message sequence chart in Figure 126 shows the scenario for transmitting a single frame of data from an originator to a recipient with an acknowledgment. In this case, the originator indicates to the recipient that it requires an acknowledgment by transmitting the data frame with the Acknowledgment Request (AR) subfield of the Frame Control field set to one.

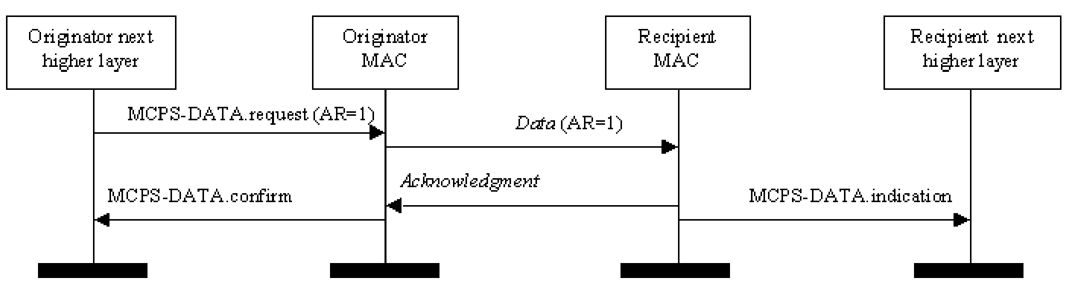


Figure 126—Successful data transmission with an acknowledgment

9.7.7.4.3 Retransmissions

A device that sends a frame with the Acknowledgment Request subfield of its Frame Control field set to zero shall assume that the transmission was successfully received and shall hence not perform the retransmission procedure.

A device that sends a data or MAC command frame with its Acknowledgment Request subfield set to one shall wait for at most *macAckWaitDuration* symbols for the corresponding acknowledgment frame to be received. If an acknowledgment frame is received within *macAckWaitDuration* symbols and contains the same DSN as the original transmission, the transmission is considered successful, and no further action regarding retransmission shall be taken by the device. If an acknowledgment is not received within *macAckWaitDuration* symbols or an acknowledgment is received containing a DSN that was not the same as the original transmission, the device shall conclude that the single transmission attempt has failed.

If a single transmission attempt has failed and the transmission was indirect, the coordinator shall not retransmit the data or MAC command frame. Instead, the frame shall remain in the transaction queue of the coordinator and can only be extracted following the reception of a new data request command. If a new data request command is received, the originating device shall transmit the frame using the same DSN as was used in the original transmission.

If a single transmission attempt has failed and the transmission was direct, the device shall repeat the process of transmitting the data or MAC command frame and waiting for the acknowledgment, up to a maximum of *macMaxFrameRetries* times. The retransmitted frame shall contain the same DSN as was used in the original transmission. Each retransmission shall only be attempted if it can be completed within the same portion of the superframe, i.e., the CAP or a GTS in which the original transmission was attempted. If this timing is not possible, the retransmission shall be deferred until the same portion in the next superframe. If an acknowledgment is still not received after *macMaxFrameRetries* retransmissions, the MAC sublayer shall assume the transmission has failed and notify the next higher layer of the failure.

9.7.7.5 Promiscuous mode

A device may activate promiscuous mode by setting *macPromiscuousMode*. If the MLME is requested to set *macPromiscuousMode* to TRUE, the MLME shall then request that the PHY enable its receiver. This request is achieved when the MLME issues the PLME-SET-TRX-STATE.request primitive with a state of RX_ON.

When in promiscuous mode, the MAC sublayer shall process received frames according to 9.7.7.2 and pass all frames correctly received to the next higher layer using the MCPS-DATA.indication primitive. The source and destination addressing mode parameters shall each be set to 0x00, the MSDU parameter shall contain the MHR concatenated with the MAC payload (see Figure 51), and the msduLength parameter shall contain the total number of octets in the MHR concatenated with the MAC payload. The mpduLinkQuality shall be valid.

If the MLME is requested to set *macPromiscuousMode* to FALSE, the MLME shall request that the PHY set its receiver to the state specified by *macRxOnWhenIdle*. This is achieved by the MLME issuing the PLME-SET-TRX-STATE.request primitive (see 6.2.2.7) with the state set accordingly.

9.7.7.6 Transmission scenarios

Due to the imperfect nature of the radio medium, a transmitted frame does not always reach its intended destination. Figure 127 illustrates three different data transmission scenarios:

— *Successful data transmission.* The originator MAC sublayer transmits the data frame to the recipient via the PHY data service. In waiting for an acknowledgment, the originator MAC sublayer starts a timer that will expire after *macAckWaitDuration* symbols. The recipient MAC sublayer receives the data frame, sends an acknowledgment back to the originator, and passes the data frame to the next higher layer. The originator MAC sublayer receives the acknowledgment from the recipient before its timer expires and then disables and resets the timer. The data transfer is now complete, and the originator MAC sublayer issues a success confirmation to the next higher layer.

— *Lost data frame.* The originator MAC sublayer transmits the data frame to the recipient via the PHY data service. In waiting for an acknowledgment, the originator MAC sublayer starts a timer that will expire after *macAckWaitDuration* symbols. The recipient MAC sublayer does not receive the data frame and so does not respond with an acknowledgment. The timer of the originator MAC sublayer expires before an acknowledgment is received; therefore, the data transfer has failed. If the transmission was direct, the originator retransmits the data, and this entire sequence may be repeated up to a maximum of *macMaxFrameRetries* times; if a data transfer attempt fails a total of (1 + *macMaxFrameRetries*) times, the originator MAC sublayer will issue a failure confirmation to the next higher layer. If the transmission was indirect, the data frame will remain in the transaction queue until either another request for the data is received and correctly acknowledged or until *macTransactionPersistenceTime* is reached. If *macTransactionPersistenceTime* is reached, the transaction information will be discarded, and the MAC sublayer will issue a failure confirmation to the next higher layer.

— *Lost acknowledgment frame.* The originator MAC sublayer transmits the data frame to the recipient via the PHY data service. In waiting for an acknowledgment, the originator MAC sublayer starts a timer that will expire after *macAckWaitDuration* symbols. The recipient MAC sublayer receives the data frame, sends an acknowledgment back to the originator, and passes the data frame to the next higher layer. The originator MAC sublayer does not receive the acknowledgment frame, and its timer expires. Therefore, the data transfer has failed. If the transmission was direct, the originator retransmits the data, and this entire sequence may be repeated up to a maximum of *macMaxFrameRetries* times. If a data transfer attempt fails a total of (1 + *macMaxFrameRetries*) times, the originator MAC sublayer will issue a failure confirmation to the next higher layer. If the transmission was indirect, the data frame will remain in the transaction queue either until another request for the data is received and correctly acknowledged or until *macTransactionPersistenceTime* is reached. If *macTransactionPersistenceTime* is reached, the transaction information will be discarded, and the MAC sublayer will issue a failure confirmation to the next higher layer.

9.7.8 GTS allocation and management

A GTS allows a device to operate on the channel within a portion of the superframe that is dedicated (on the WPAN) exclusively to that device. A GTS shall be allocated only by the coordinator, and it shall be used only for communications between the coordinator and a device associated with the VLC WPAN through the coordinator. A single GTS may extend over one or more superframe slots. The coordinator may allocate a number of GTSs at the same time, provided there is sufficient capacity in the superframe.

A GTS shall be allocated before use, with the coordinator deciding whether to allocate a GTS based on the requirements of the GTS request and the current available capacity in the superframe. GTSs shall be allocated on a first-come-first-served basis, and all GTSs shall be placed contiguously at the end of the superframe and after the CAP. Each GTS shall be deallocated when the GTS is no longer required, and a GTS can be deallocated at any time at the discretion of the coordinator or by the device that originally requested the GTS. A device that has been allocated a GTS may also operate in the CAP.

A data frame transmitted in an allocated GTS shall use only short addressing.

The management of GTSs shall be undertaken by the coordinator only. To facilitate GTS management, the coordinator shall be able to store all the information necessary to manage seven GTSs. For each GTS, the coordinator shall be able to store its starting slot, length, direction, and associated device address.

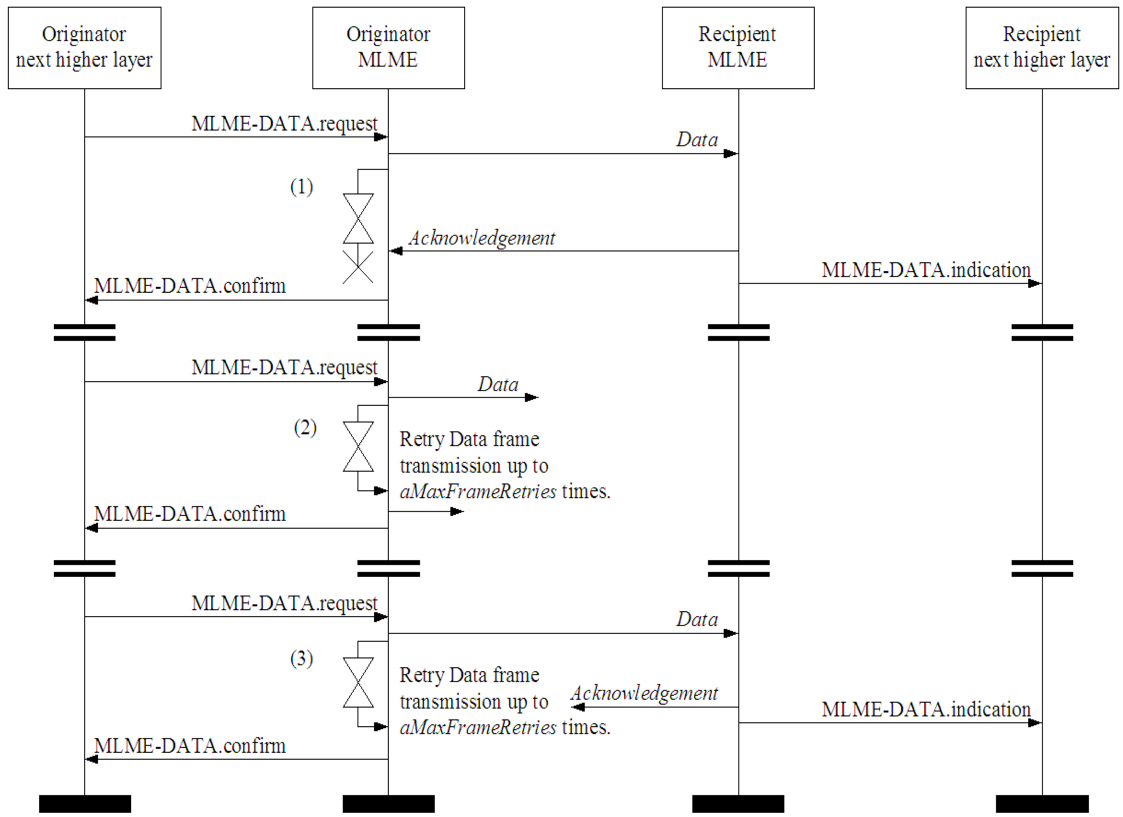


Figure 127—Transmission scenarios, using direct transmission, for frame reliability

The GTS direction, which is relative to the data flow from the device that owns the GTS, is specified as either transmit or receive. The device address and direction shall, therefore, uniquely identify each GTS. Each device may request one transmit GTS and/or one receive GTS. For each allocated GTS, the device shall be able to store its starting slot, length, and direction. If a device has been allocated a receive GTS, it shall enable its receiver for the entirety of the GTS. In the same way, the coordinator shall enable its receiver for the entirety of the GTS if a device has been allocated a transmit GTS. If a data frame is received during a receive GTS and an acknowledgment is requested, the device shall transmit the acknowledgment frame as usual. Similarly, a device shall be able to receive an acknowledgment frame during a transmit GTS.

A device shall attempt to allocate and use a GTS only if it is currently tracking the beacons. The MLME is instructed to track beacons by issuing the MLME-SYNC.request primitive with the TrackBeacon parameter set to TRUE. If a device loses synchronization with the coordinator, all its GTS allocations shall be lost.

The use of GTSs is optional.

9.7.8.1 CAP maintenance

The coordinator shall preserve the minimum CAP length of *aMinCAPLength* and take preventative action if the minimum CAP is not satisfied. However, an exception shall be allowed for the accommodation of the temporary increase in the beacon frame length needed to perform GTS maintenance. If preventative action becomes necessary, the action chosen is left up to the implementation, but may include one or more of the following:

— Limiting the number of pending addresses included in the beacon.

— Not including a payload field in the beacon frame.

— Deallocating one or more of the GTSs.

9.7.8.2 GTS allocation

A device is instructed to request the allocation of a new GTS through the MLME-GTS.request primitive, with GTS characteristics set according to the requirements of the intended application.

To request the allocation of a new GTS, the MLME shall send the GTS request command (see 7.4.13) to the coordinator. The Characteristics Type subfield of the GTS Characteristics field of the request shall be set to one (GTS allocation), and the length and direction subfields shall be set according to the desired characteristics of the required GTS. Because the GTS request command contains an acknowledgment request (see 7.4.3.1), the coordinator shall confirm its receipt by sending an acknowledgment frame.

On receipt of a GTS request command indicating a GTS allocation request, the coordinator shall first check if there is available capacity in the current superframe, based on the remaining length of the CAP and the desired length of the requested GTS. The superframe shall have available capacity if the maximum number of GTSs has not been reached and allocating a GTS of the desired length would not reduce the length of the CAP to less than *aMinCAPLength*. GTSs shall be allocated on a first-come-first-served basis by the coordinator provided there is sufficient bandwidth available. The coordinator shall make this decision within *aGTSDescPersistenceTime* superframes.

On receipt of the acknowledgment to the GTS request command, the device shall continue to track beacons and wait for at most *aGTSDescPersistenceTime* superframes. If no GTS descriptor for the device appears in the beacon within this time, the MLME of the device shall notify the next higher layer of the failure. This notification is achieved when the MLME issues the MLME-GTS.confirm primitive (see 7.1.7.2) with a status of NO_DATA.

When the coordinator determines whether capacity is available for the requested GTS, it shall generate a GTS descriptor with the requested specifications and the 16-bit short address of the requesting device. If the GTS was allocated successfully, the coordinator shall set the start slot in the GTS descriptor to the superframe slot at which the GTS begins and the length in the GTS descriptor to the length of the GTS. In addition, the coordinator shall notify the next higher layer of the new GTS. This notification is achieved when the MLME of the coordinator issues the MLME-GTS.indication primitive (see 7.1.7.3) with the characteristics of the allocated GTS. If there was not sufficient capacity to allocate the requested GTS, the start slot shall be set to zero and the length to the largest GTS length that can currently be supported. The coordinator shall then include this GTS descriptor in its beacon and update the GTS Specification field of the beacon frame accordingly. The coordinator shall also update the Final CAP Slot subfield of the Superframe Specification field of the beacon frame, indicating the final superframe slot utilized by the decreased CAP. The GTS descriptor shall remain in the beacon frame for *aGTSDescPersistenceTime* superframes, after which it shall be removed automatically. The coordinator shall be allowed to reduce its CAP below *aMinCAPLength* to accommodate the temporary increase in the beacon frame length due to the inclusion of the GTS descriptor.

On receipt of a beacon frame containing a GTS descriptor corresponding to *macShortAddress*, the device shall process the descriptor. The MLME of the device shall then notify the next higher layer of whether the GTS allocation request was successful. This notification is achieved when the MLME issues the MLME-GTS.confirm primitive with a status of SUCCESS (if the start slot in the GTS descriptor was greater than zero) or DENIED (if the start slot was equal to zero or if the length did not match the requested length).

9.7.8.3 GTS usage

When the MAC sublayer of a device that is not the coordinator receives an MCPS-DATA.request primitive (see 7.1.1.1) with the TxOptions parameter indicating a GTS transmission, it shall determine whether it has a valid transmit GTS. If a valid GTS is found, the MAC sublayer shall transmit the data during the GTS, i.e., between its starting slot and its starting slot plus its length. At this time, the MAC sublayer shall transmit the MPDU immediately without using random access, provided the requested transaction can be completed before the end of the GTS. If the requested transaction cannot be completed before the end of the current GTS, the MAC sublayer shall defer the transmission until the specified GTS in the next superframe. Note that the MAC must allow for the PHY overhead (see 6.9.2.2) in making this determination.

If the device has any receive GTSs, the MAC sublayer of the device shall ensure that the receiver is enabled at a time prior to the start of the GTS and for the duration of the GTS, as indicated by its starting slot and its length.

When the MAC sublayer of the coordinator receives an MCPS-DATA.request primitive with the TxOptions parameter indicating a GTS transmission, it shall determine whether it has a valid receive GTS corresponding to the device with the requested destination address. If a valid GTS is found, the coordinator shall defer the transmission until the start of the receive GTS. In this case, the address of the device with the message requiring a GTS transmission shall not be added to the list of pending addresses in the beacon frame (see 9.7.6). At the start of the receive GTS, the MAC sublayer shall transmit the data without using random access, provided the requested transaction can be completed before the end of the GTS. If the requested transaction cannot be completed before the end of the current GTS, the MAC sublayer shall defer the transmission until the specified GTS in the next superframe.

For all allocated transmit GTSs (relative to the device), the MAC sublayer of the coordinator shall ensure that its receiver is enabled at a time prior to the start and for the duration of each GTS.

Before commencing transmission in a GTS, each device shall ensure that the data transmission, the acknowledgment, if requested, and the IFS, suitable to the size of the data frame, can be completed before the end of the GTS.

If a device misses the beacon at the beginning of a superframe, it shall not use its GTSs until it receives a subsequent beacon correctly. If a loss of synchronization occurs due to the loss of the beacon, the device shall consider all of its GTSs deallocated.

9.7.8.4 GTS deallocation

A device is instructed to request the deallocation of an existing GTS through the MLME-GTS.request primitive (see 7.1.7.1), using the characteristics of the GTS it wishes to deallocate. From this point onward, the GTS to be deallocated shall not be used by the device, and its stored characteristics shall be reset.

To request the deallocation of an existing GTS, the MLME shall send the GTS request command (see 7.4.13) to the coordinator. The Characteristics Type subfield of the GTS Characteristics field of the request shall be set to zero (i.e., GTS deallocation), and the length and direction subfields shall be set according to the characteristics of the GTS to deallocate. Because the GTS request command contains an acknowledgment request (see 7.4.3.1), the coordinator shall confirm its receipt by sending an acknowledgment frame. On receipt of the acknowledgment to the GTS request command, the MLME shall notify the next higher layer of the deallocation. This notification is achieved when the MLME issues the MLME-GTS.confirm primitive (see 7.1.7.2) with a status of SUCCESS and a GTSCharacteristics parameter with its Characteristics Type subfield set to zero. If the GTS request command is not received correctly by the coordinator, it shall determine that the device has stopped using its GTS by the procedure described in 9.7.8.6.

On receipt of a GTS request command with the Characteristics Type subfield of the GTS Characteristics field set to zero (GTS deallocation), the coordinator shall attempt to deallocate the GTS. If the GTS characteristics contained in the GTS request command do not match the characteristics of a known GTS, the coordinator shall ignore the request. If the GTS characteristics contained in the GTS request command match the characteristics of a known GTS, the MLME of the coordinator shall deallocate the specified GTS and notify the next higher layer of the change. This notification is achieved when the MLME issues the MLME-GTS.indication primitive (see 7.1.7.3) with a GTSCharacteristics parameter containing the characteristics of the deallocated GTS and a Characteristics Type subfield set to zero. The coordinator shall also update the Final CAP Slot subfield of the Superframe Specification field of the beacon frame, indicating the final superframe slot utilized by the increased CAP. It shall not add a descriptor to the beacon frame to describe the deallocation.

GTS deallocation may be initiated by the coordinator due to a deallocation request from the next higher layer, the expiration of the GTS (see 9.7.8.6), or maintenance required to maintain the minimum CAP length, *aMinCAPLength* (see 9.7.8.1).

When a GTS deallocation is initiated by the next higher layer of the coordinator, the MLME shall receive the MLME-GTS.request primitive with the GTS Characteristics field of the request set to zero (i.e., GTS deallocation) and the length and direction subfields set according to the characteristics of the GTS to deallocate.

When a GTS deallocation is initiated by the coordinator either due to the GTS expiring or due to CAP maintenance, the MLME shall notify the next higher layer of the change. This notification is achieved when the MLME issues the MLME-GTS.indication primitive with a GTSCharacteristics parameter containing the characteristics of the deallocated GTS and a Characteristics Type subfield set to zero.

In the case of any deallocation initiated by coordinator, the coordinator shall deallocate the GTS and add a GTS descriptor into its beacon frame corresponding to the deallocated GTS, but with its starting slot set to zero. The descriptor shall remain in the beacon frame for *aGTSDescPersistenceTime* superframes. The coordinator shall be allowed to reduce its CAP below *aMinCAPLength* to accommodate the temporary increase in the beacon frame length due to the inclusion of the GTS descriptor.

On receipt of a beacon frame containing a GTS descriptor corresponding to *macShortAddress* and a start slot equal to zero, the device shall immediately stop using the GTS. The MLME of the device shall then notify the next higher layer of the deallocation. This notification is achieved when the MLME issues the MLME-GTS.indication primitive with a GTSCharacteristics parameter containing the characteristics of the deallocated GTS and a Characteristics Type subfield set to zero.

9.7.8.5 GTS reallocation

The deallocation of a GTS may result in the superframe becoming fragmented. For example, Figure 128 shows three stages of a superframe with allocated GTSs. In stage 1, three GTSs are allocated starting at slots 14, 10, and 8, respectively. If GTS 2 is now deallocated (stage 2), there will be a gap in the superframe during which nothing can happen. To solve this, GTS 3 will have to be shifted to fill the gap, thus increasing the size of the CAP (stage 3).

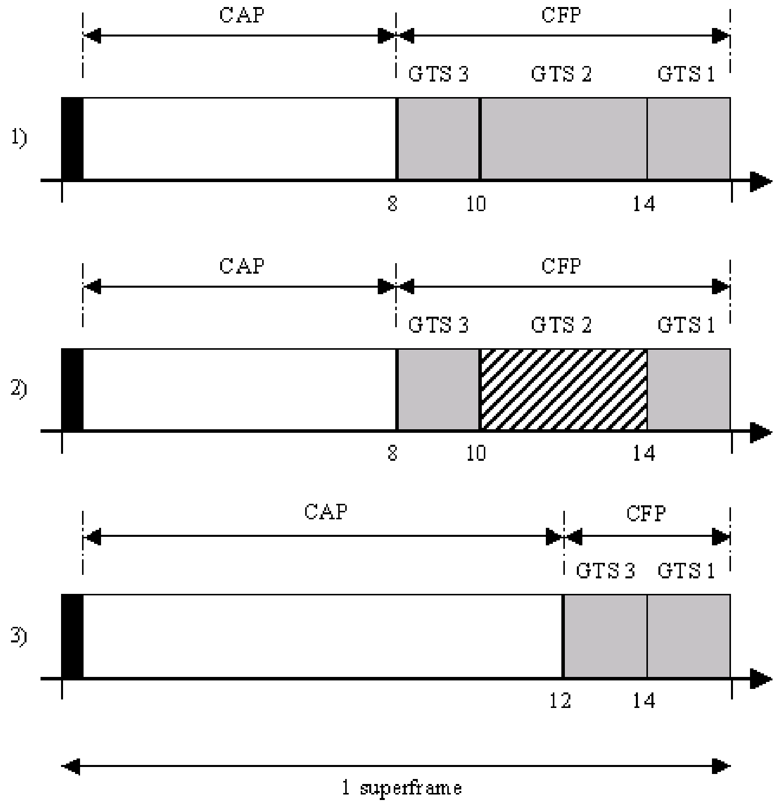


Figure 128—CFP defragmentation on GTS deallocations

The coordinator shall ensure that any gaps occurring in the CFP, appearing due to the deallocation of a GTS, are removed to maximize the length of the CAP.

When a GTS is deallocated by the coordinator, it shall add a GTS descriptor into its beacon frame indicating that the GTS has been deallocated. If the deallocation is initiated by a device, the coordinator shall not add a GTS descriptor into its beacon frame to indicate the deallocation. For each device with an allocated GTS having a starting slot lower than the GTS being deallocated, the coordinator shall update the GTS with the new starting slot and add a GTS descriptor to its beacon corresponding to this adjusted GTS. The new starting slot is computed so that no space is left between this GTS and either the end of the CFP, if the GTS appears at the end of the CFP, or the start of the next GTS in the CFP.

In situations where multiple reallocations occur at the same time, the coordinator may choose to perform the reallocation in stages. The coordinator shall keep each GTS descriptor in its beacon for *aGTSDescPersistenceTime* superframes.

On receipt of a beacon frame containing a GTS descriptor corresponding to *macShortAddress* and a direction and length corresponding to one of its GTSs, the device shall adjust the starting slot of the GTS corresponding to the GTS descriptor and start using it immediately.

In cases where it is necessary for the coordinator to include a GTS descriptor in its beacon, it shall be allowed to reduce its CAP below *aMinCAPLength* to accommodate the temporary increase in the beacon frame length. After *aGTSDescPersistenceTime* superframes, the coordinator shall remove the GTS descriptor from the beacon.

9.7.8.6 GTS expiration

The MLME of the coordinator shall attempt to detect when a device has stopped using a GTS using the following rules:

- For a transmit GTS, the MLME of the coordinator shall assume that a device is no longer using its GTS if a data frame is not received from the device in the GTS at least every 2**n* superframes, where *n* is defined below.
- For receive GTSs, the MLME of the coordinator shall assume that a device is no longer using its GTS if an acknowledgment frame is not received from the device at least every 2**n* superframes, where *n* is defined below. If the data frames sent in the GTS do not require acknowledgment frames, the MLME of the coordinator will not be able to detect whether a device is using its receive GTS. However, the coordinator is capable of deallocating the GTS at any time.

The value of *n* is defined as follows:

$$n = 2^{(8-macBeaconOrder)} \qquad 0 \le macBeaconOrder \le 8$$

$$n = 1 \qquad 9 \le macBeaconOrder \le 14$$

9.7.9 Frame security

[Editor's Note" this section and the security mechanism needs to be reviewed for its applicability to VLC]

The MAC sublayer is responsible for providing security services on specified incoming and outgoing frames when requested to do so by the higher layers. This standard supports the following security services (see 5.5.6 for definitions):

- Data confidentiality
- Data authenticity
- Replay protection

The information determining how to provide the security is found in the security-related PIB (see Table 78 in 9.8.1).

9.7.9.1 Security-related MAC PIB attributes

The security-related MAC PIB attributes contain:

- Key table (*macKeyTable*, *macKeyTableEntries*)
- Device table (*macDeviceTable*, *macDeviceTableEntries*)
- Minimum security level table (*macSecurityLevelTable*, *macSecurityLevelTableEntries*)
- Frame counter (*macFrameCounter*)
- Automatic request attributes (*macAutoRequestSecurityLevel*, *macAutoRequestKeyIdMode*, *macAutoRequestKeySource*, *macAutoRequestKeyIndex*)
- Default key source (*macDefaultKeySource*)
- coordinator address (*macWPANCoordExtendedAddress, macWPANCoordShortAddress*)

9.7.9.1.1 Key table

The key table holds key descriptors (keys with related key-specific information) that are required for security processing of outgoing and incoming frames. Key-specific information in the key table is identified based on information explicitly contained in the requesting primitive or in the received frame, as described in the outgoing frame key retrieval procedure (see 9.7.9.2.2) and the incoming frame security material retrieval procedure (see 9.7.9.2.4), as well as in the KeyDescriptor lookup procedure (see 9.7.9.2.5).

9.7.9.1.2 Device table

The device table holds device descriptors (device-specific addressing information and security-related information) that, when combined with key-specific information from the key table, provide all the keying material needed to secure outgoing (see 9.7.9.2.1) and unsecure incoming frames (see 9.7.9.2.3). Device-specific information in the device table is identified based on the originator of the frame, as described in the DeviceDescriptor lookup procedure (see 9.7.9.2.7), and on key-specific information, as described in the blacklist checking procedure (see 9.7.9.2.6).

9.7.9.1.3 Minimum security level table

The minimum security level table holds information regarding the minimum security level the device expects to have been applied by the originator of a frame, depending on frame type and, if it concerns a MAC command frame, the command frame identifier. Security processing of an incoming frame will fail if the frame is not adequately protected, as described in the incoming frame security procedure (see 9.7.9.2.3) and in the incoming security level checking procedure (see 9.7.9.2.8).

9.7.9.1.4 Frame counter

The 4-octet frame counter is used to provide replay protection and semantic security of the cryptographic building block used for securing outgoing frames. The frame counter is included in each secured frame and is one of the elements required for the unsecuring operation at the recipient(s). The frame counter is incremented each time an outgoing frame is secured, as described in the outgoing frame security procedure (see 9.7.9.2.1). When the frame counter reaches its maximum value of 0xffffffff, the associated keying material can no longer be used, thus requiring all keys associated with the device to be updated. This provides a mechanism for ensuring that the keying material for every frame is unique and, thereby, provides for sequential freshness.

9.7.9.1.5 Automatic request attributes

Automatic request attributes hold all the information needed to secure outgoing frames generated automatically and not as a result of a higher layer primitive, as is the case with automatic data requests.

9.7.9.1.6 Default key source

The default key source is information commonly shared between originator and receipient(s) of a secured frame, which, when combined with additional information explicitly contained in the requesting primitive or in the received frame, allows an originator or a recipient to determine the key required for securing or unsecuring this frame, respectively. This provides a mechanism for significantly reducing the overhead of security information contained in secured frames in particular use cases (see 9.7.9.2.2 and 9.7.9.2.4).

9.7.9.1.7 Coordinator address

The address of the coordinator is information commonly shared between all devices in a VLC WPAN, which, when combined with additional information explicitly contained in the requesting primitive or in the received frame, allows an originator of a frame directed to the coordinator or a recipient of a frame originating from the coordinator to determine the key and security-related information required for securing or unsecuring, respectively, this frame (see 9.7.9.2.2 and 9.7.9.2.4).

9.7.9.2 Functional description

A device may optionally implement security. A device that does not implement security shall not provide a mechanism for the MAC sublayer to perform any cryptographic transformation on incoming and outgoing frames nor require any PIB attributes associated with security. A device that implements security shall provide a mechanism for the MAC sublayer to provide cryptographic transformations on incoming and outgoing frames using information in the PIB attributes associated with security when the *macSecurityEnabled* attribute is set to TRUE.

If the MAC sublayer is required to transmit a frame or receives an incoming frame, the MAC sublayer shall process the frame as specified in 9.7.9.2.1 and 9.7.9.2.3, respectively.

9.7.9.2.1 Outgoing frame security procedure

The inputs to this procedure are the frame to be secured and the SecurityLevel, KeyIdMode, KeySource, and KeyIndex parameters from the originating primitive or automatic request PIB attributes. The outputs from this procedure are the status of the procedure and, if this status is SUCCESS, the secured frame.

The outgoing frame security procedure involves the following steps as applicable:

a) If the Security Enabled subfield of the Frame Control field of the frame to be secured is set to zero, the procedure shall set the security level to zero.

b) If the Security Enabled subfield of the Frame Control field of the frame to be secured is set to one, the procedure shall set the security level to the SecurityLevel parameter. If the resulting security level is zero, the procedure shall return with a status of UNSUPPORTED_SECURITY.

c) If the *macSecurityEnabled* attribute is set to FALSE and the security level is not equal to zero, the procedure shall return with a status of UNSUPPORTED_SECURITY.

d) The procedure shall determine whether the frame to be secured satisfies the constraint on the maximum length of MAC frames, as follows:

    1) The procedure shall set the length *M*, in octets, of the Authentication field to zero if the security level is equal to zero and shall determine this value from the security level and Table 85 otherwise.

    2) The procedure shall determine the length AuxLen, in octets, of the auxiliary security header (see 9.8.2) using KeyIdMode and the security level.

    3) The procedure shall determine the data expansion as AuxLen + *M*.

    4) The procedure shall check whether the length of the frame to be secured, including data expansion and FCS, is less than or equal to *aMaxPHYPacketSize*. If this check fails, the procedure shall return with a status of FRAME_TOO_LONG.

e) If the security level is zero, the procedure shall set the secured frame to be the frame to be secured and return with the secured frame and a status of SUCCESS.

f) The procedure shall set the frame counter to the *macFrameCounter* attribute. If the frame counter has the value 0xffffffff, the procedure shall return with a status of COUNTER_ERROR.

g) The procedure shall obtain the key using the outgoing frame key retrieval procedure as described in 9.7.9.2.2. If that procedure fails, the procedure shall return with a status of UNAVAILABLE_KEY.

h) The procedure shall insert the auxiliary security header into the frame, with fields set as follows:

    1) The Security Level subfield of the Security Control field shall be set to the security level.

    2) The Key Identifier Mode subfield of the Security Control field shall be set to the KeyIdMode parameter.

    3) The Frame Counter field shall be set to the frame counter.

4) If the KeyIdMode parameter is set to a value not equal to zero, the Key Source and Key Index subfields of the Key Identifier field shall be set to the KeySource and KeyIndex parameters, respectively.

i) The procedure shall then use *aExtendedAddress*, the frame counter, the security level, and the key to produce the secured frame according to the transformation process known as CCM* [or the extension of CCM, which is the combined counter with CBC-MAC (i.e., cipher block chaining message authentication code) mode of operation] that is described in the security operations (see 9.8.3.4).

   1) If the SecurityLevel parameter specifies the use of encryption (see Table 85 in 9.8.2.2.1), the encryption operation shall be applied only to the actual payload field within the MAC payload, i.e., the Beacon Payload field (see 7.2.2.1.8), Command Payload field (see 7.2.2.6.3), or Data Payload field (see 7.2.2.4.2), depending on the frame type. The corresponding payload field is passed to the CCM* transformation process described in 9.8.3.4 as the unsecured payload (see Table 87 in 9.8.3.4.2). The resulting encrypted payload shall substitute the original payload.

   2) The remaining fields in the MAC payload part of the frame shall be passed to the CCM* transformation process described in 9.8.3.4 as the nonpayload fields (see Table 87).

   3) The ordering and exact manner of performing the encryption and integrity operations and the placement of the resulting encrypted data or integrity code within the MAC Payload field shall be as defined in 9.8.3.4.

j) The procedure shall increment the frame counter by one and set the *macFrameCounter* attribute to the resulting value.

k) The procedure shall return with the secured frame and a status of SUCCESS.

9.7.9.2.2 Outgoing frame key retrieval procedure

The inputs to this procedure are the frame to be secured and the KeyIdMode, KeySource, and KeyIndex parameters from the originating primitive. The outputs from this procedure are a passed or failed status and, if passed, a key.

The outgoing frame key retrieval procedure involves the following steps as applicable:

a) If the KeyIdMode parameter is set to 0x00 (implicit key identification), the procedure shall determine the key lookup data and key lookup size as follows:

   1) If the Destination Addressing Mode subfield of the Frame Control field of the frame is set to 0x00 and the *macWPANCoordShortAddress* attribute is set to a value in the range 0x0000–0xfffd (i.e., the short address is used), the key lookup data shall be set to the 2-octet Source WPAN Identifier field of the frame right-concatenated (see B.2.1) with the 2-octet *macWPANCoordShortAddress* attribute right-concatenated with the single octet 0x00. The key lookup size shall be set to five.

   2) If the Destination Addressing Mode subfield of the Frame Control field of the frame is set to 0x00 and the *macWPANCoordShortAddress* attribute is set to 0xfffe (i.e., the extended address is used), the key lookup data shall be set to the 8-octet *macWPANCoordExtendedAddress* attribute right-concatenated (see B.2.1) with the single octet 0x00. The key lookup size shall be set to nine.

   3) If the Destination Addressing Mode subfield of the Frame Control field of the frame is set to 0x02, the key lookup data shall be set to the 2-octet Destination WPAN Identifier field of the frame right-concatenated (see B.2.1) with the 2-octet Destination Address field of the frame right-concatenated with the single octet 0x00. The key lookup size shall be set to five.

   4) If the Destination Addressing Mode subfield of the Frame Control field of the frame is set to 0x03, the key lookup data shall be set to the 8-octet Destination Address field of the frame right-concatenated (see B.2.1) with the single octet 0x00. The key lookup size shall be set to nine.

b) If the KeyIdMode parameter is set to a value not equal to 0x00 (explicit key identification), the procedure shall determine the key lookup data and key lookup size as follows:
   1) If the KeyIdMode parameter is set to 0x01, the key lookup data shall be set to the 8-octet *macDefaultKeySource* attribute right-concatenated (see B.2.1) with the single octet KeyIndex parameter. The key lookup size shall be set to nine.
   2) If the KeyIdMode parameter is set to 0x02, the key lookup data shall be set to the 4-octet KeySource parameter right-concatenated (see B.2.1) with the single octet KeyIndex parameter. The key lookup size shall be set to five.
   3) If the KeyIdMode parameter is set to 0x03, the key lookup data shall be set to the 8-octet KeySource parameter right-concatenated (see B.2.1) with the single octet KeyIndex parameter. The key lookup size shall be set to nine.

c) The procedure shall obtain the KeyDescriptor by passing the key lookup data and the key lookup size to the KeyDescriptor lookup procedure as described in 9.7.9.2.5. If that procedure returns with a failed status, this procedure shall also return with a failed status.

d) The MAC sublayer shall set the key to the Key element of the KeyDescriptor.

e) The procedure shall return with a passed status, having obtained the key identifier and the key.

NOTE—For broadcast frames, the outgoing frame key retrieval procedure will result in a failed status if implicit key identification is used. Hence, explicit key identification should be used for broadcast frames.[1]

9.7.9.2.3 Incoming frame security procedure

The input to this procedure is the frame to be unsecured. The outputs from this procedure are the unsecured frame, the security level, the key identifier mode, the key source, the key index, and the status of the procedure. All outputs of this procedure are assumed to be invalid unless and until explicitly set in this procedure. It is assumed that the PIB attributes associating KeyDescriptors in *macKeyTable* with a single, unique device or a number of devices will have been established by the next higher layer.

The incoming frame security procedure involves the following steps as applicable:

a) If the Security Enabled subfield of the Frame Control field of the frame to be unsecured is set to zero, the procedure shall set the security level to zero.

b) If the Security Enabled subfield of the Frame Control field of the frame to be unsecured is set to one and the Frame Version subfield of the Frame Control field of the frame to be unsecured is set to zero, the procedure shall set the unsecured frame to be the frame to be unsecured and return with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of UNSUPPORTED_LEGACY.

c) If the Security Enabled subfield of the Frame Control field of the frame to be unsecured is set to one, the procedure shall set the security level and the key identifier mode to the corresponding subfields of the Security Control field of the auxiliary security header of the frame to be unsecured and shall set the key source and key index to the corresponding subfields of the Key Identifier field of the auxiliary security header of the frame to be unsecured, if present. If the resulting security level is zero, the procedure shall set the unsecured frame to be the frame to be unsecured and return with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of UNSUPPORTED_SECURITY.

d) If the *macSecurityEnabled* attribute is set to FALSE, the procedure shall set the unsecured frame to be the frame to be unsecured and return with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of SUCCESS if the security level is equal to zero and with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of UNSUPPORTED_SECURITY otherwise.

[1]Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

e) The procedure shall determine whether the frame to be unsecured meets the minimum security level by passing the security level, the frame type, and, depending on whether the frame is a MAC command frame, the first octet of the MAC payload (i.e., command frame identifier for a MAC command frame) to the incoming security level checking procedure as described in 9.7.9.2.8. If that procedure fails, the procedure shall set the unsecured frame to be the frame to be unsecured and return with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of IMPROPER_SECURITY_LEVEL.

f) If the security level is set to zero, the procedure shall set the unsecured frame to be the frame to be unsecured and return with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of SUCCESS.

g) The procedure shall obtain the KeyDescriptor, DeviceDescriptor, and KeyDeviceDescriptor using the incoming frame security material retrieval procedure described in 9.7.9.2.4. If that procedure fails, the procedure shall set the unsecured frame to be the frame to be unsecured and return with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of UNAVAILABLE_KEY.

h) The procedure shall determine whether the frame to be unsecured conforms to the key usage policy by passing the KeyDescriptor, the frame type, and, depending on whether the frame is a MAC command frame, the first octet of the MAC payload (i.e., command frame identifier for a MAC command frame) to the incoming key usage policy checking procedure as described in 9.7.9.2.9. If that procedure fails, the procedure shall set the unsecured frame to be the frame to be unsecured and return with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of IMPROPER_KEY_TYPE.

i) If the Exempt element of the DeviceDescriptor is set to FALSE and if the incoming security level checking procedure of Step e) above had as output the "conditionally passed" status, the procedure shall set the unsecured frame to be the frame to be unsecured and return with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of IMPROPER_SECURITY_LEVEL.

j) The procedure shall set the frame counter to the Frame Counter field of the auxiliary security header of the frame to be unsecured. If the frame counter has the value 0xffffffff, the procedure shall set the unsecured frame to be the frame to be unsecured and return with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of COUNTER_ERROR.

k) The procedure shall determine whether the frame counter is greater than or equal to the FrameCounter element of the DeviceDescriptor. If this check fails, the procedure shall set the unsecured frame to be the frame to be unsecured and return with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of COUNTER_ERROR.

l) The procedure shall then use the ExtAddress element of the DeviceDescriptor, the frame counter, the security level, and the Key element of the KeyDescriptor to produce the unsecured frame according to the CCM* inverse transformation process described in the security operations (see 9.8.3.5).

    1) If the security level specifies the use of encryption (see Table 85 in 9.8.2.2.1), the decryption operation shall be applied only to the actual payload field within the MAC payload, i.e., the Beacon Payload field (see 7.2.2.1.8), Command Payload field (see 7.2.2.6.3), or Data Payload field (see 7.2.2.4.2), depending on the frame type. The corresponding payload field shall be passed to the CCM* inverse transformation process described in 9.8.3.5 as the secure payload.

    2) The remaining fields in the MAC payload part of the frame shall be passed to the CCM* inverse transformation process described in 9.8.3.5 as the nonpayload fields.

m) If the CCM* inverse transformation process fails, the procedure shall set the unsecured frame to be the frame to be unsecured and return with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of SECURITY_ERROR.

n) The procedure shall increment the frame counter by one and set the FrameCounter element of the DeviceDescriptor to the resulting value.

o) If the FrameCounter element is equal to 0xffffffff, the procedure shall set the Blacklisted element of the KeyDeviceDescriptor.

p) The procedure shall return with the unsecured frame, the security level, the key identifier mode, the key source, the key index, and a status of SUCCESS.

9.7.9.2.4 Incoming frame security material retrieval procedure

The input to this procedure is the frame to be unsecured. The outputs from this procedure are a passed or failed status and, if passed, a KeyDescriptor, a DeviceDescriptor, and a KeyDeviceDescriptor.

The incoming frame security material retrieval procedure involves the following steps as applicable:

a) If the Key Identifier Mode subfield of the Security Control field of the auxiliary security header of the frame is set to 0x00 (implicit key identification), the procedure shall determine the key lookup data and the key lookup size as follows:
   1) If the source address mode of the Frame Control field of the frame is set to 0x00 and the *macWPANCoordShortAddress* attribute is set to a value in the range 0x0000–0xfffd (i.e., the short address is used), the key lookup data shall be set to the 2-octet Destination WPAN Identifier field of the frame right-concatenated (see B.2.1) with the 2-octet *macWPANCoordShortAddress* attribute right-concatenated with the single octet 0x00. The key lookup size shall be set to five.
   2) If the source address mode of the Frame Control field of the frame is set to 0x00 and the *macWPANCoordShortAddress* attribute is set to 0xfffe (i.e., the extended address is used), the key lookup data shall be set to the 8-octet *macWPANCoordExtendedAddress* attribute right-concatenated (see B.2.1) with the single octet 0x00. The key lookup size shall be set to nine.
   3) If the source address mode of the Frame Control field of the frame is set to 0x02, the key lookup data shall be set to the 2-octet Source WPAN Identifier field of the frame, or to the 2-octet Destination WPAN Identifier field of the frame if the WPAN ID Compression subfield of the Frame Control field of the frame is set to one, right-concatenated (see B.2.1) with the 2-octet Source Address field of the frame right-concatenated with the single octet 0x00. The key lookup size shall be set to five.
   4) If the source address mode of the Frame Control field of the frame is set to 0x03, the key lookup data shall be set to the 8-octet Source Address field of the frame right-concatenated (see B.2.1) with the single octet 0x00. The key lookup size shall be set to nine.

b) If the Key Identifier Mode subfield of the Security Control field of the auxiliary security header of the frame is set to a value not equal to 0x00 (explicit key identification), the procedure shall determine the key lookup data and key lookup size as follows:
   1) If the key identifier mode is set to 0x01, the key lookup data shall be set to the 8-octet *macDefaultKeySource* attribute right-concatenated (see B.2.1) with the 1-octet Key Index subfield of the Key Identifier field of the auxiliary security header. The key lookup size shall be set to nine.
   2) If the key identifier mode is set to 0x02, the key lookup data shall be set to the right-concatenation (see B.2.1) of the 4-octet Key Source subfield and the 1-octet Key Index subfield of the Key Identifier field of the auxiliary security header. The key lookup size shall be set to five.
   3) If the key identifier mode is set to 0x03, the key lookup data shall be set to the right-concatenation (see B.2.1) of the 8-octet Key Source subfield and the 1-octet Key Index subfield of the Key Identifier field of the auxiliary security header. The key lookup size shall be set to nine.

c) The procedure shall obtain the KeyDescriptor by passing the key lookup data and the key lookup size to the KeyDescriptor lookup procedure as described in 9.7.9.2.5. If that procedure returns with a failed status, the procedure shall also return with a failed status.

d) The procedure shall determine the device lookup data and the device lookup size as follows:
   1) If the source address mode of the Frame Control field of the frame is set to 0x00 and the *macWPANCoordShortAddress* attribute is set to a value in the range 0x0000–0xfffd (i.e., the short address is used), the device lookup data shall be set to the 2-octet Destination WPAN Identifier field of the frame right-concatenated (see B.2.1) with the 2-octet *macWPANCoordShortAddress* attribute. The device lookup size shall be set to four.
   2) If the source address mode of the Frame Control field of the frame is set to 0x00 and the *macWPANCoordShortAddress* attribute is set to 0xfffe (i.e., the extended address is used), the device lookup data shall be set to the 8-octet *macWPANCoordExtendedAddress* attribute. The device lookup size shall be set to eight.
   3) If the source address mode of the Frame Control field of the frame is set to 0x02, the device lookup data shall be set to the 2-octet Source WPAN Identifier field of the frame, or to the 2-octet Destination WPAN Identifier field of the frame if the WPAN ID Compression subfield of the Frame Control field of the frame is set to one, right-concatenated (see B.2.1) with the 2-octet Source Address field of the frame. The device lookup size shall be set to four.
   4) If the source address mode of the Frame Control field of the frame is set to 0x03, the device lookup data shall be set to the 8-octet Source Address field of the frame. The device lookup size shall be set to eight.

e) The procedure shall obtain the DeviceDescriptor and the KeyDeviceDescriptor by passing the KeyDescriptor, the device lookup data, and the device lookup size to the blacklist checking procedure as described in 9.7.9.2.6. If that procedure returns with a failed status, the procedure shall also return with a failed status.

f) The procedure shall return with a passed status having obtained the KeyDescriptor, the DeviceDescriptor, and the KeyDeviceDescriptor.

9.7.9.2.5 KeyDescriptor lookup procedure

The inputs to this procedure are the key lookup data and the key lookup size. The outputs from this procedure are a passed or failed status and, if passed, a KeyDescriptor.

The KeyDescriptor lookup procedure involves the following steps as applicable:

a) For each KeyDescriptor in the *macKeyTable* attribute and for each KeyIdLookupDescriptor in the KeyIdLookupList of the KeyDescriptor, the procedure shall check whether the LookupDataSize element of the KeyIdLookupDescriptor indicates the same integer value (see Figure 84) as the key lookup size and whether the LookupData element of the KeyIdLookupDescriptor is equal to the key lookup data. If both checks pass (i.e., there is a match), the procedure shall return with this (matching) KeyDescriptor and a passed status.

b) The procedure shall return with a failed status.

9.7.9.2.6 Blacklist checking procedure

The inputs to this procedure are the KeyDescriptor, the device lookup data, and the device lookup size. The outputs from this procedure are a passed or failed status and, if passed, a DeviceDescriptor and a KeyDeviceDescriptor.

The blacklist checking procedure involves the following steps as applicable:

a) For each KeyDeviceDescriptor in the KeyDeviceList of the KeyDescriptor:
   1) The procedure shall obtain the DeviceDescriptor using the DeviceDescriptorHandle element of the KeyDeviceDescriptor.
   2) If the UniqueDevice element of the KeyDeviceDescriptor is set to TRUE, the procedure shall return with the DeviceDescriptor, the KeyDeviceDescriptor, and a passed status if the

BlackListed element of the KeyDeviceDescriptor is set to FALSE, or the procedure shall return with a failed status if this Blacklisted element is set to TRUE.

3) If the UniqueDevice element of the KeyDeviceDescriptor is set to FALSE, the procedure shall execute the DeviceDescriptor lookup procedure as described in 9.7.9.2.7, with the device lookup data and the device lookup size as inputs. If the corresponding output of that procedure is a passed status, the procedure shall return with the DeviceDescriptor, the KeyDeviceDescriptor, and a passed status if the Blacklisted element of the KeyDeviceDescriptor is set to FALSE, or the procedure shall return with a failed status if this Blacklisted element is set to TRUE.

b) The procedure shall return with a failed status.

9.7.9.2.7 DeviceDescriptor lookup procedure

The inputs to this procedure are the DeviceDescriptor, the device lookup data, and the device lookup size. The output from this procedure is a passed or failed status.

The DeviceDescriptor lookup procedure involves the following steps as applicable:

a) If the device lookup size is four and the device lookup data is equal to the WPAN ID element of the DeviceDescriptor right-concatenated (see B.2.1) with the ShortAddress element of the DeviceDescriptor, this procedure shall return with a passed status.
b) If the device lookup size is eight and the device lookup data is equal to the ExtAddress element of the DeviceDescriptor, this procedure shall return with a passed status.
c) The procedure shall return with a failed status.

9.7.9.2.8 Incoming security level checking procedure

The inputs to this procedure are the incoming security level, the frame type and the command frame identifier. The output from this procedure is a passed, failed, or “conditionally passed” status.

The incoming security level checking procedure involves the following steps as applicable:

a) For each SecurityLevelDescriptor in the *macSecurityLevelTable* attribute:
   1) If the frame type is not equal to 0x03 and the frame type is equal to the FrameType element of the SecurityLevelDescriptor, the procedure shall compare the incoming security level (as SEC1) with the SecurityMinimum element of the SecurityLevelDescriptor (as SEC2) according to the algorithm described in 9.8.2.2.1. If this comparison fails (i.e., evaluates to FALSE), the procedure shall return with a “conditionally passed” status if the DeviceOverrideSecurityMinimum element of the SecurityLevelDescriptor is set to TRUE and the security level is set to zero and with a failed status otherwise.
   2) If the frame type is equal to 0x03, the frame type is equal to the FrameType element of the SecurityLevelDescriptor, and the command frame identifier is equal to the CommandFrameIdentifier element of the SecurityLevelDescriptor, the procedure shall compare the incoming security level (as SEC1) with the SecurityMinimum element of the SecurityLevelDescriptor (as SEC2) according to the algorithm described in 9.8.2.2.1. If this comparison fails (i.e., evaluates to FALSE), the procedure shall return with a “conditionally passed” status if the DeviceOverrideSecurityMinimum element of the SecurityLevelDescriptor is set to TRUE and the security level is set to zero and with a failed status otherwise.
b) The procedure shall return with a passed status.

9.7.9.2.9 Incoming key usage policy checking procedure

The inputs to this procedure are the KeyDescriptor, the frame type, and the command frame identifier. The output from this procedure is a passed or failed status.

The incoming key usage policy checking procedure involves the following steps as applicable:

a) For each KeyUsageDescriptor in the KeyUsageList of the KeyDescriptor:

   1) If the frame type is not equal to 0x03 and the frame type is equal to the FrameType element of the KeyUsageDescriptor, the procedure shall return with a passed status.

   2) If the frame type is equal to 0x03, the frame type is equal to the FrameType element of the KeyUsageDescriptor, and the command frame identifier is equal to the CommandFrame-Identifier element of the KeyUsageDescriptor, the procedure shall return with a passed status.

b) The procedure shall return with a failed status.

9.8 Security suite specifications

[Editor's Note: this section and the security mechanism needs to be reviewed for its applicability to VLC]

9.8.1 PIB security material

The PIB security-related attributes are presented in Table 78, Table 79, Table 80, Table 81, Table 82, Table 83, and Table 84.

Table 78— Security-related MAC PIB attributes

Attribute	Identifier	Type	Range	Description	Default
macKeyTable	0x71	List of Key-Descriptor entries (see Table 79)	—	A table of KeyDescriptor entries, each containing keys and related information required for secured communications.	(empty)
macKeyTableEntries	0x72	Integer	Implementa-tion specific	The number of entries in *macKeyTable*.	0
macDeviceTable	0x73	List of Device-Descriptor entries (see Table 83)	—	A table of Device-Descriptor entries, each indicating a remote device with which this device securely communicates.	(empty)
macDeviceTable-Entries	0x74	Integer	Implementa-tion specific	The number of entries in *macDeviceTable*.	0
macSecurity-LevelTable	0x75	Table of SecurityLevel Descriptor entries (see Table 82)	—	A table of SecurityLevel-Descriptor entries, each with information about the minimum security level expected depending on incoming frame type and subtype.	(empty)
macSecurity-LevelTableEntries	0x76	Integer	Implementa-tion specific	The number of entries in *macSecurityLevelTable*.	0
macFrameCounter	0x77	Integer	0x00000000–0xffffffff	The outgoing frame counter for this device.	0x00000000
macAutoRequest-SecurityLevel	0x78	Integer	0x00–0x07	The security level used for automatic data requests.	0x06

Table 78— Security-related MAC PIB attributes *(continued)*

Attribute	Identifier	Type	Range	Description	Default
macAutoRequest-KeyIdMode	0x79	Integer	0x00–0x03	The key identifier mode used for automatic data requests. This attribute is invalid if the *macAuto-RequestSecurityLevel* attribute is set to 0x00.	0x00
macAutoRequest-KeySource	0x7a	As specified by the *mac-AutoRequest-KeyIdMode* parameter	—	The originator of the key used for automatic data requests. This attribute is invalid if the *macAuto-RequestKeyIdMode* element is invalid or set to 0x00.	All octets 0xff
macAutoRequest-KeyIndex	0x7b	Integer	0x01–0xff	The index of the key used for automatic data requests. This attribute is invalid if the *macAuto-RequestKeyIdMode* attribute is invalid or set to 0x00.	All octets 0xff
macDefaultKey-Source	0x7c	Set of 8 octets	—	The originator of the default key used for key identifier mode 0x01.	All octets 0xff
macWPANCoord-ExtendedAddress	0x7d	IEEE address	An extended 64-bit IEEE address	The 64-bit address of the coordinator.	—
macWPANCoordSho rt-Address	0x7e	Integer	0x0000–0xffff	The 16-bit short address assigned to the coordinator. A value of 0xfffe indicates that the coordinator is only using its 64-bit extended address. A value of 0xffff indicates that this value is unknown.	0x0000

Table 79—Elements of KeyDescriptor

Name	Type	Range	Description
KeyIdLookupList	List of KeyId-LookupDescriptor entries (see Table 84)	—	A list of KeyIdLookupDescriptor entries used to identify this KeyDescriptor.
KeyIdLookupListEntries	Integer	Implementation specific	The number of entries in KeyIdLookupList.
KeyDeviceList	List of KeyDevice-Descriptor entries (see Table 81)	—	A list of KeyDeviceDescriptor entries indicating which devices are currently using this key, including their blacklist status.
KeyDeviceListEntries	Integer	Implementation specific	The number of entries in KeyDeviceList.

Table 79—Elements of KeyDescriptor *(continued)*

Name	Type	Range	Description
KeyUsageList	List of KeyUsage-Descriptor entries (see Table 80)	—	A list of KeyUsageDescriptor entries indicating which frame types this key may be used with.
KeyUsageListEntries	Integer		The number of entries in KeyUsageList.
Key	Set of 16 octets	—	The actual value of the key.

Table 80—Elements of KeyUsageDescriptor

Name	Type	Range	Description
FrameType	Integer	0x00–0x03	See 7.2.1.1.1.
CommandFrameIdentifier	Integer	0x00–0x09	See Table 66.

Table 81—Elements of KeyDeviceDescriptor

Name	Type	Range	Description
DeviceDescriptorHandle	Integer	Implementa-tion specific	Handle to the DeviceDescriptor corresponding to the device (see Table 83).
UniqueDevice	Boolean	TRUE or FALSE	Indication of whether the device indicated by DeviceDescriptorHandle is uniquely associated with the KeyDescriptor, i.e., it is a link key as opposed to a group key.
Blacklisted	Boolean	TRUE or FALSE	Indication of whether the device indicated by DeviceDescriptorHandle previously communicated with this key prior to the exhaustion of the frame counter. If TRUE, this indicates that the device shall not use this key further because it exhausted its use of the frame counter used with this key.

9.8.2 Auxiliary security header

The Auxiliary Security Header field has a variable length and contains information required for security processing, including a Security Control field, a Frame Counter field, and a Key Identifier field. The Auxiliary Security Header field shall be present only if the Security Enabled subfield of the Frame Control field is set to one. The Auxiliary Security Header field shall be formatted as illustrated in Figure 129.

9.8.2.1 Integer and octet representation

The auxiliary security header is a MAC frame field (see 7.2.1.7) and, therefore, uses the representation conventions specified in 7.2.

Table 82—Elements of SecurityLevelDescriptor

Name	Type	Range	Description
FrameType	Integer	0x00–0x03	See 7.2.1.1.1.
CommandFrameIdentifier	Integer	0x00–0x09	See Table 66.
SecurityMinimum	Integer	0x00–0x07	The minimal required/expected security level for incoming MAC frames with the indicated frame type and, if present, command frame type (see Table 85 in 9.8.2.2.1).
DeviceOverrideSecurity-Minimum	Boolean	TRUE or FALSE	Indication of whether originating devices for which the Exempt flag is set may override the minimum security level indicated by the SecurityMinimum element. If TRUE, this indicates that for originating devices with Exempt status, the incoming security level zero is acceptable, in addition to the incoming security levels meeting the minimum expected security level indicated by the SecurityMinimum element.

Table 83—Elements of DeviceDescriptor

Name	Type	Range	Description
WPANId	Device WPAN ID	0x0000–0xffff	The 16-bit WPAN identifier of the device in this DeviceDescriptor.
ShortAddress	Device short address	0x0000–0xffff	The 16-bit short address of the device in this DeviceDescriptor. A value of 0xfffe indicates that this device is using only its extended address. A value of 0xffff indicates that this value is unknown.
ExtAddress	IEEE address	Any valid 64-bit device address	The 64-bit IEEE extended address of the device in this DeviceDescriptor. This element is also used in unsecuring operations on incoming frames.
FrameCounter	Integer	0x00000000–0xffffffff	The incoming frame counter of the device in this DeviceDescriptor. This value is used to ensure sequential freshness of frames.
Exempt	Boolean	TRUE or FALSE	Indication of whether the device may override the minimum security level settings defined in Table 82.

9.8.2.2 Security Control field

The Security Control field is 1 octet in length and is used to provide information about what protection is applied to the frame. The Security Control field shall be formatted as shown in Figure 130.

Table 84—Elements of KeyIdLookupDescriptor

Name	Type	Range	Description
LookupData	Set of 5 or 9 octets	—	Data used to identify the key.
LookupDataSize	Integer	0x00–0x01	A value of 0x00 indicates a set of 5 octets; a value of 0x01 indicates a set of 9 octets.

Octets: 1	4	0/1/5/9
Security Control	Frame Counter	Key Identifier

Figure 129—Format of the auxiliary security header

Bit: 0–2	3–4	5–7
Security Level	Key Identifier Mode	Reserved

Figure 130—Security Control field format

9.8.2.2.1 Security Level subfield

The Security Level subfield is 3 bits in length and indicates the actual frame protection that is provided. This value can be adapted on a frame-by-frame basis and allows for varying levels of data authenticity (to allow minimization of security overhead in transmitted frames where required) and for optional data confidentiality. The cryptographic protection offered by the various security levels is shown in Table 85. When nontrivial protection is required, replay protection is always provided.

Table 85—Security levels available to the MAC sublayer

Security level identifier	Security Control field (Figure 130) b_2 b_1 b_0	Security attributes	Data confidentiality	Data authenticity (including length *M* of authentication tag, in octets)
0x00	'000'	None	OFF	NO ($M = 0$)
0x01	'001'	MIC-32	OFF	YES ($M = 4$)
0x02	'010'	MIC-64	OFF	YES ($M = 8$)
0x03	'011'	MIC-128	OFF	YES ($M = 16$)
0x04	'100'	ENC	ON	NO ($M = 0$)
0x05	'101'	ENC-MIC-32	ON	YES ($M = 4$)
0x06	'110'	ENC-MIC-64	ON	YES ($M = 8$)
0x07	'111'	ENC-MIC-128	ON	YES ($M = 16$)

Security levels can be ordered according to the corresponding cryptographic protection offered. Here, a first security level SEC1 is greater than or equal to a second security level SEC2 if and only if SEC1 offers at least the protection offered by SEC2, both with respect to data confidentiality and with respect to data authenticity. The statement "SEC1 is greater than or equal to SEC2" shall be evaluated as TRUE if both of the following conditions apply:

a) Bit position b_2 in SEC1 is greater than or equal to bit position b_2 in SEC2 (where Encryption OFF < Encryption ON).

b) The integer value of bit positions b_1 b_0 in SEC1 is greater than or equal to the integer value of bit positions b_1 b_0 in SEC2 (where increasing integer values indicate increasing levels of data authenticity provided, i.e., message integrity code (MIC)-0 < MIC-32 < MIC-64 < MIC-128).

Otherwise, the statement shall be evaluated as FALSE.

For example, ENC-MIC-64 ≥ MIC-64 is TRUE because ENC-MIC-64 offers the same data authenticity protection as MIC-64, plus confidentiality. On the other hand, MIC-128 ≥ ENC-MIC-64 is FALSE because even though MIC-128 offers stronger data authenticity than ENC-MIC-64, it offers no confidentiality.

9.8.2.2.2 Key Identifier Mode subfield

The Key Identifier Mode subfield is 2 bits in length and indicates whether the key that is used to protect the frame can be derived implicitly or explicitly; furthermore, it is used to indicate the particular representations of the Key Identifier field (see 9.8.2.4) if derived explicitly. The Key Identifier Mode subfield shall be set to one of the values listed in Table 86. The Key Identifier field of the auxiliary security header (see 9.8.2.4) shall be present only if this subfield has a value that is not equal to 0x00.

Table 86—Values of the key identifier mode

Key identifier mode	Key Identifier Mode subfield b_1 b_0	Description	Key Identifier field length (octets)
0x00	'00'	Key is determined implicitly from the originator and receipient(s) of the frame, as indicated in the frame header.	0
0x01	'01'	Key is determined from the 1-octet Key Index subfield of the Key Identifier field of the auxiliary security header in conjunction with *macDefaultKeySource*.	1
0x02	'10'	Key is determined explicitly from the 4-octet Key Source subfield and the 1-octet Key Index subfield of the Key Identifier field of the auxiliary security header.	5
0x03	'11'	Key is determined explicitly from the 8-octet Key Source subfield and the 1-octet Key Index subfield of the Key Identifier field of the auxiliary security header.	9

9.8.2.3 Frame Counter field

The Frame Counter field is 4 octets in length and represents the *macFrameCounter* attribute of the originator of a protected frame. It is used to provide semantic security of the cryptographic mechanism used to protect a frame and to offer replay protection.

9.8.2.4 Key Identifier field

The Key Identifier field has a variable length and identifies the key that is used for cryptographic protection of outgoing frames, either explicitly or in conjunction with implicitly defined side information. The Key Identifier field shall be present only if the Key Identifier Mode subfield of the Security Control field of the auxiliary security header (see 9.8.2.2.2) is set to a value different from 0x00. The Key Identifier field shall be formatted as illustrated in Figure 131.

Octets: 0/4/8	**1**
Key Source	Key Index

Figure 131—Format for the Key Identifier field, if present

9.8.2.4.1 Key Source subfield

The Key Source subfield, when present, is either 4 octets or 8 octets in length, according to the value specified by the Key Identifier Mode subfield of the Security Control field (see 9.8.2.2.2), and indicates the originator of a group key.

9.8.2.4.2 Key Index subfield

The Key Index subfield is 1 octet in length and allows unique identification of different keys with the same originator.

It is the responsibility of each key originator to make sure that actively used keys that it issues have distinct key indices and that the key indices are all different from 0x00.

9.8.3 Security operations

This subclause describes the parameters for the CCM* security operations, as specified in B.3.2.

9.8.3.1 Integer and octet representation

The integer and octet representation conventions specified in B.2 are used throughout 9.8.3.

9.8.3.2 CCM* Nonce

The CCM* nonce is a 13-octet string and is used for the advanced encryption standard (AES)-CCM* mode of operation (see B.2.2). The nonce shall be formatted as shown in Figure 132, with the leftmost field in the figure defining the first (and leftmost) octets and the rightmost field defining the last (and rightmost) octet of the nonce.

The source address shall be set to the extended address *aExtendedAddress* of the device originating the frame, the frame counter to the value of the respective field in the auxiliary security header (see 9.8.2), and

Octets: 8	4	1
Source address	Frame counter	Security level

Figure 132—CCM* nonce

the security level to the security level identifier corresponding to the Security Level subfield of the Security Control field of the auxiliary security header as defined in Table 85.

The source address, frame counter, and security level shall be represented as specified in 9.8.3.1.

9.8.3.3 CCM* prerequisites

Securing a frame involves the use of the CCM* mode encryption and authentication transformation, as described in B.4.1. Unsecuring a frame involves the use of the CCM* decryption and authentication checking process, as described in B.4.2. The prerequisites for the CCM* forward and inverse transformations are as follows:

- The underlying block cipher shall be the AES encryption algorithm as specified in B.3.1.
- The bit ordering shall be as defined in 9.8.3.1.
- The length in octets of the Length field L shall be 2 octets.
- The length of the Authentication field M shall be 0 octets, 4 octets, 8 octets, or 16 octets, as required.

9.8.3.3.1 Authentication field length

The length of the Authentication field M for the CCM* forward transformation and the CCM* inverse transformation is determined from Table 85, using the Security Level subfield of the Security Control field of the auxiliary security header of the frame.

9.8.3.4 CCM* transformation data representation

This subclause describes how the inputs and output of the CCM* forward transformation, as described in B.4.1, are formed:

The inputs are

- Key
- Nonce
- *a* data
- *m* data

The output is *c* data.

9.8.3.4.1 Key and nonce data inputs

The Key data for the CCM* forward transformation is passed by the outgoing frame security procedure described in 9.7.9.2.1. The Nonce data for the CCM* transformation is constructed as described in 9.8.3.2.

9.8.3.4.2 *a* data and *m* data

In the CCM* transformation process, the data fields shall be applied as in Table 87.

Table 87—*a* data and *m* data for all security levels

Security level identifier	*a* data	*m* data
0x00	None	None
0x01	MHR || Auxiliary security header || Nonpayload fields || Unsecured payload fields	None
0x02	MHR || Auxiliary security header || Nonpayload fields || Unsecured payload fields	None
0x03	MHR || Auxiliary security header || Nonpayload fields || Unsecured payload fields	None
0x04	None	Unsecured payload fields
0x05	MHR || Auxiliary security header || Nonpayload fields	Unsecured payload fields
0x06	MHR || Auxiliary security header || Nonpayload fields	Unsecured payload fields
0x07	MHR || Auxiliary security header || Nonpayload fields	Unsecured payload fields

9.8.3.4.3 *c* data output

In the CCM* transformation process, the data fields that are applied, or right-concatenated and applied, represent octet strings.

The secured payload fields right-concatenated with the authentication tag shall substitute the unsecured payload field in the original unsecured frame to form the secured frame (see Table 88).

Table 88—*c* data for all security levels

Security level identifier	*c* data
0x00	None
0x01	MIC-32
0x02	MIC-64
0x03	MIC-128
0x04	Secured payload fields
0x05	Secured payload fields || MIC-32
0x06	Secured payload fields || MIC-64
0x07	Secured payload fields || MIC-128

9.8.3.5 CCM* inverse transformation data representation

This subclause describes how the inputs and output of the CCM* inverse transformation, as described in B.4.2, are formed.

The inputs are

— Key

— Nonce
— *c* data
— *a* data

The output is *m* data.

9.8.3.5.1 Key and nonce data inputs

The Key data for the CCM* inverse transformation is passed by the incoming frame security procedure described in 9.7.9.2.3. The Nonce data for the CCM* transformation is constructed as described in 9.8.3.2.

9.8.3.5.2 *c* data and *a* data

In the CCM* inverse transformation process, the data fields shall be applied as in Table 89.

Table 89—*c* data and *a* data for all security levels

Security level identifier	*c* data	*a* data
0x00	None	None
0x01	MIC-32	MHR || Auxiliary security header || Nonpayload fields ||Secured payload fields
0x02	MIC-64	MHR || Auxiliary security header || Nonpayload fields || Secured payload fields
0x03	MIC-128	MHR || Auxiliary security header || Nonpayload fields || Secured payload fields
0x04	Secured payload fields	MHR || Auxiliary security header || Nonpayload fields
0x05	Secured payload fields || MIC-32	MHR || Auxiliary security header || Nonpayload fields
0x06	Secured payload fields || MIC-64	MHR || Auxiliary security header || Nonpayload fields
0x07	Secured payload fields || MIC-128	MHR || Auxiliary security header || Nonpayload fields

9.8.3.5.3 *m* data output

The *m* data shall then substitute secured payload fields and authentication tag in the original secured frame to form the unsecured frame.

9.9 Message sequence charts illustrating MAC-PHY interaction

[This section has not been updated to reflect changes made for VLC]

This subclause illustrates the main tasks specified in this standard. Each task is described by use of a message sequence chart to illustrate the chronological order, rather than the exact timing, of the primitives required for each task.

The primitives necessary for the coordinator to start a new WPAN are shown in Figure 133. The first action the next higher layer takes after resetting the MAC sublayer is to initiate a scan to search for other WPANs in the area. An active scan is required, and an ED scan may optionally be performed. The steps for performing an active scan and an ED scan are shown in Figure 138 and Figure 134, respectively.

Once a new WPAN is established, the coordinator is ready to accept requests from other devices to join the WPAN. Figure 135 shows the primitives issued by a device requesting association, while Figure 136 illustrates the steps taken by a coordinator allowing association. In the process of joining a WPAN, the device requesting association will perform either a passive or an active scan to determine which WPANs in the area are allowing association; Figure 137 and Figure 138 detail the primitives necessary to complete a passive scan and an active scan, respectively.

The primitives necessary for transmitting and receiving a single data packet are shown next. The actions taken by the originator of the packet are shown in Figure 139, while the actions taken by the recipient are shown in Figure 140.

When a device becomes unable to communicate to its coordinator any longer, the device can use an orphan scan to rediscover its coordinator. The primitives necessary for the realignment of an orphaned device are shown in Figure 141.

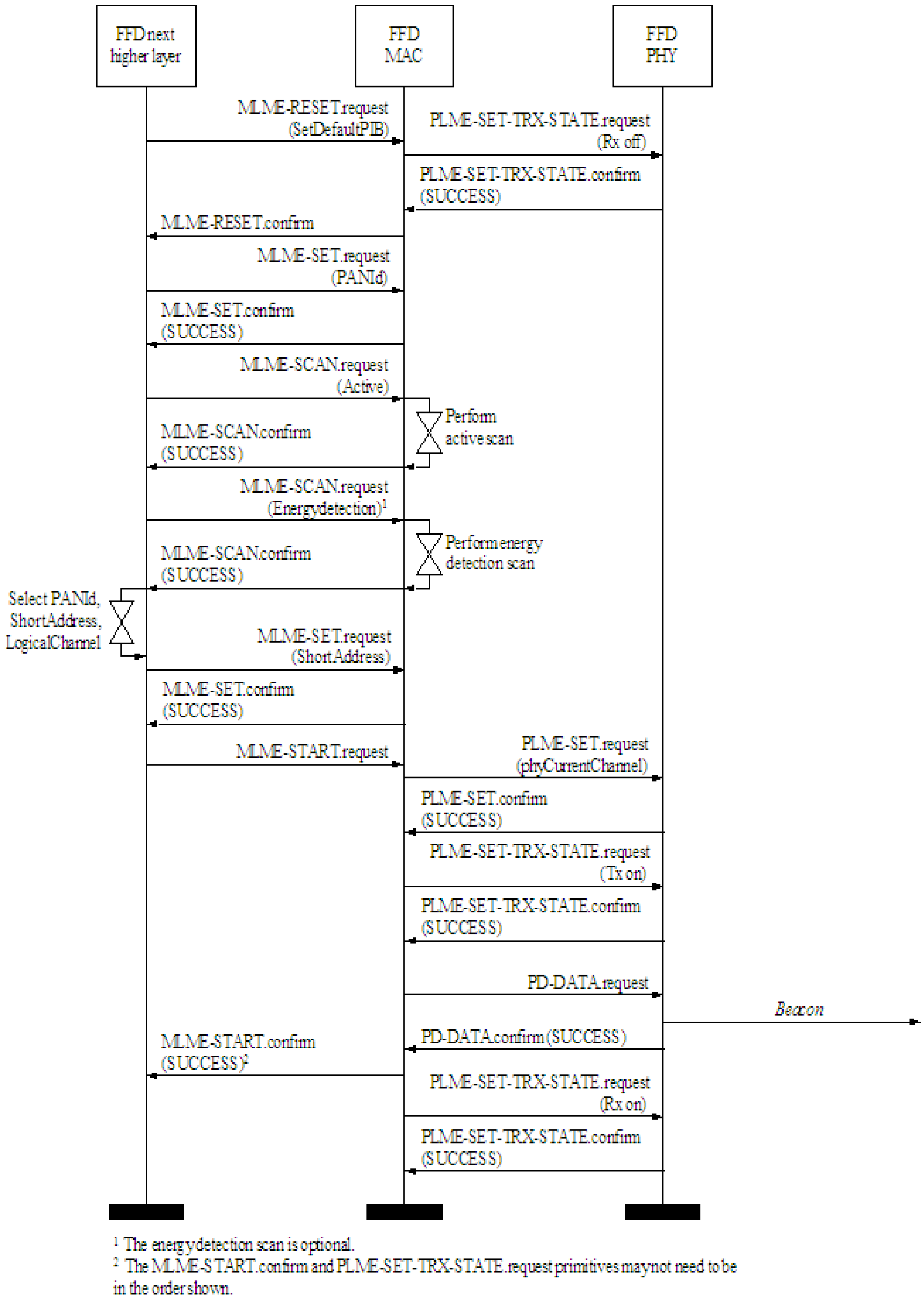


Figure 133—WPAN start message sequence chart—coordinator

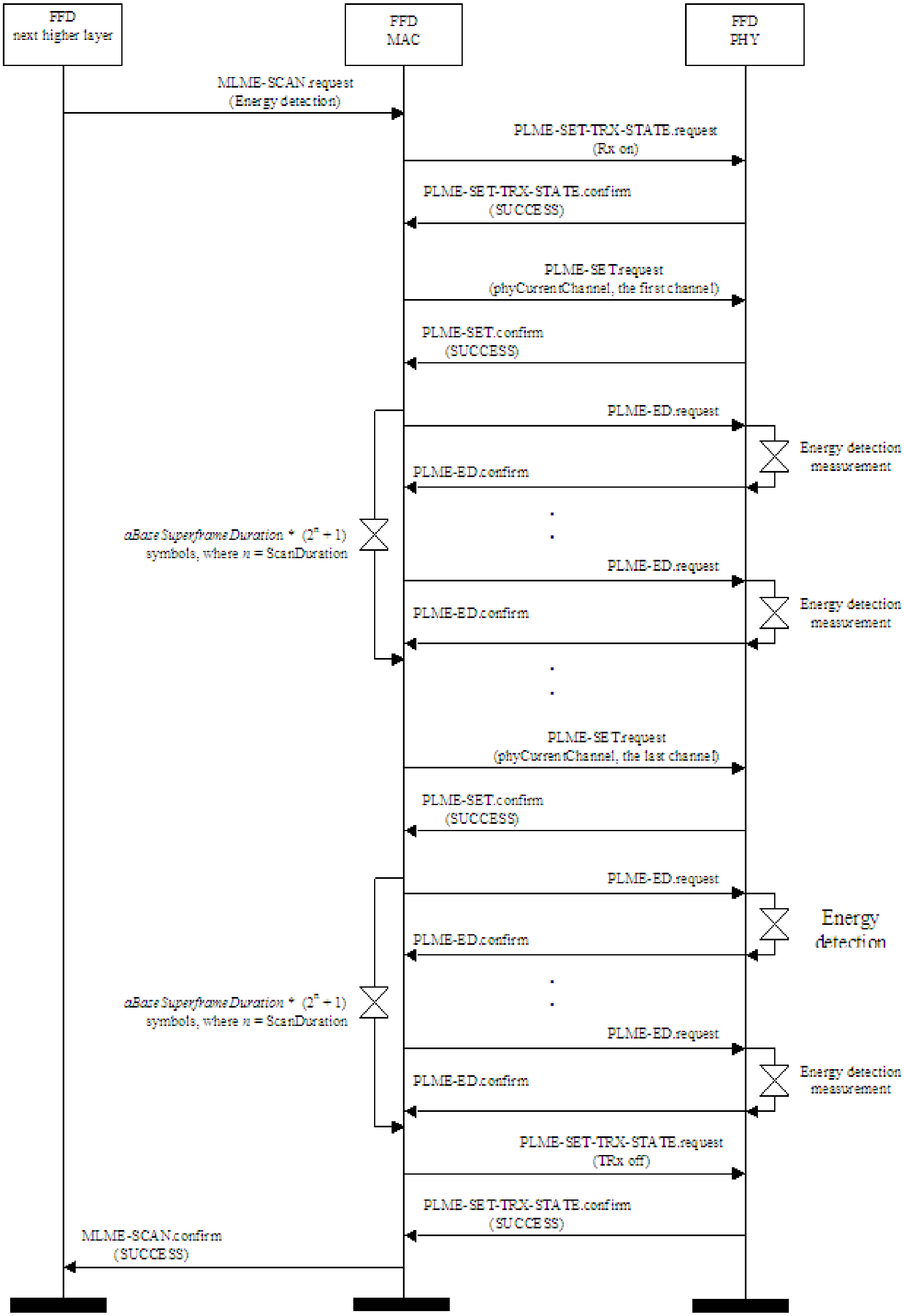


Figure 134—ED scan message sequence chart

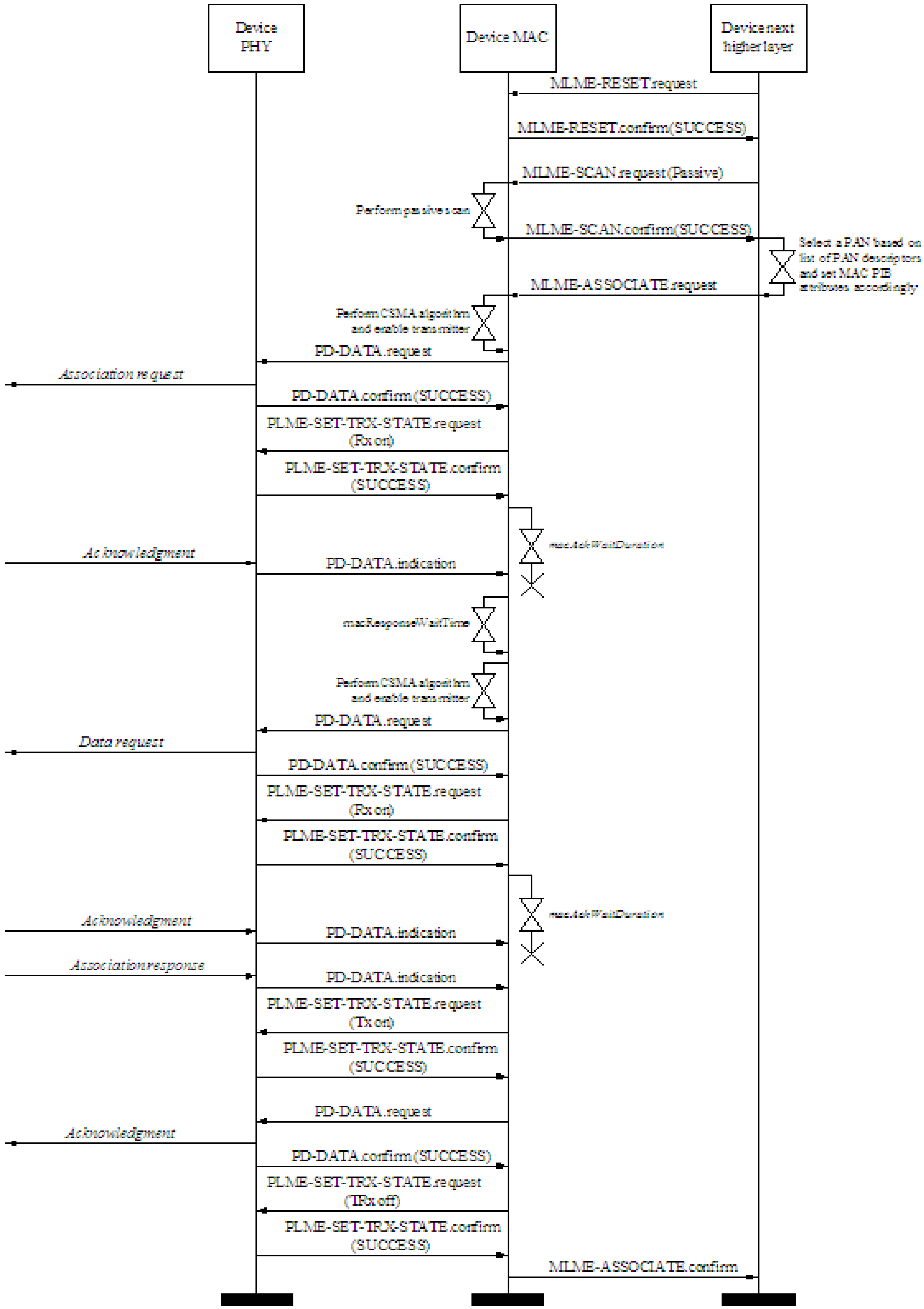


Figure 135—Association message sequence chart—device

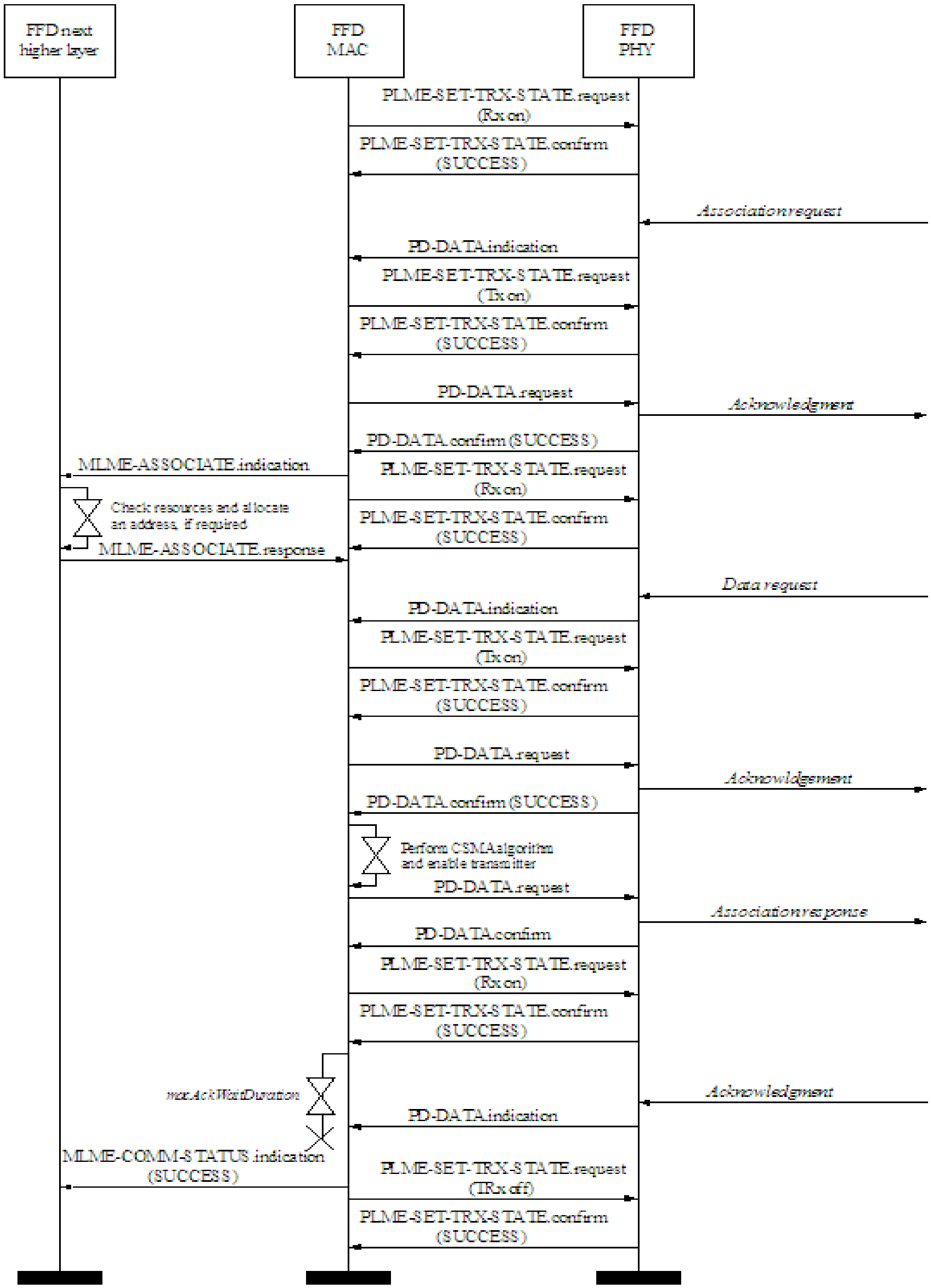


Figure 136—Association message sequence chart—coordinator

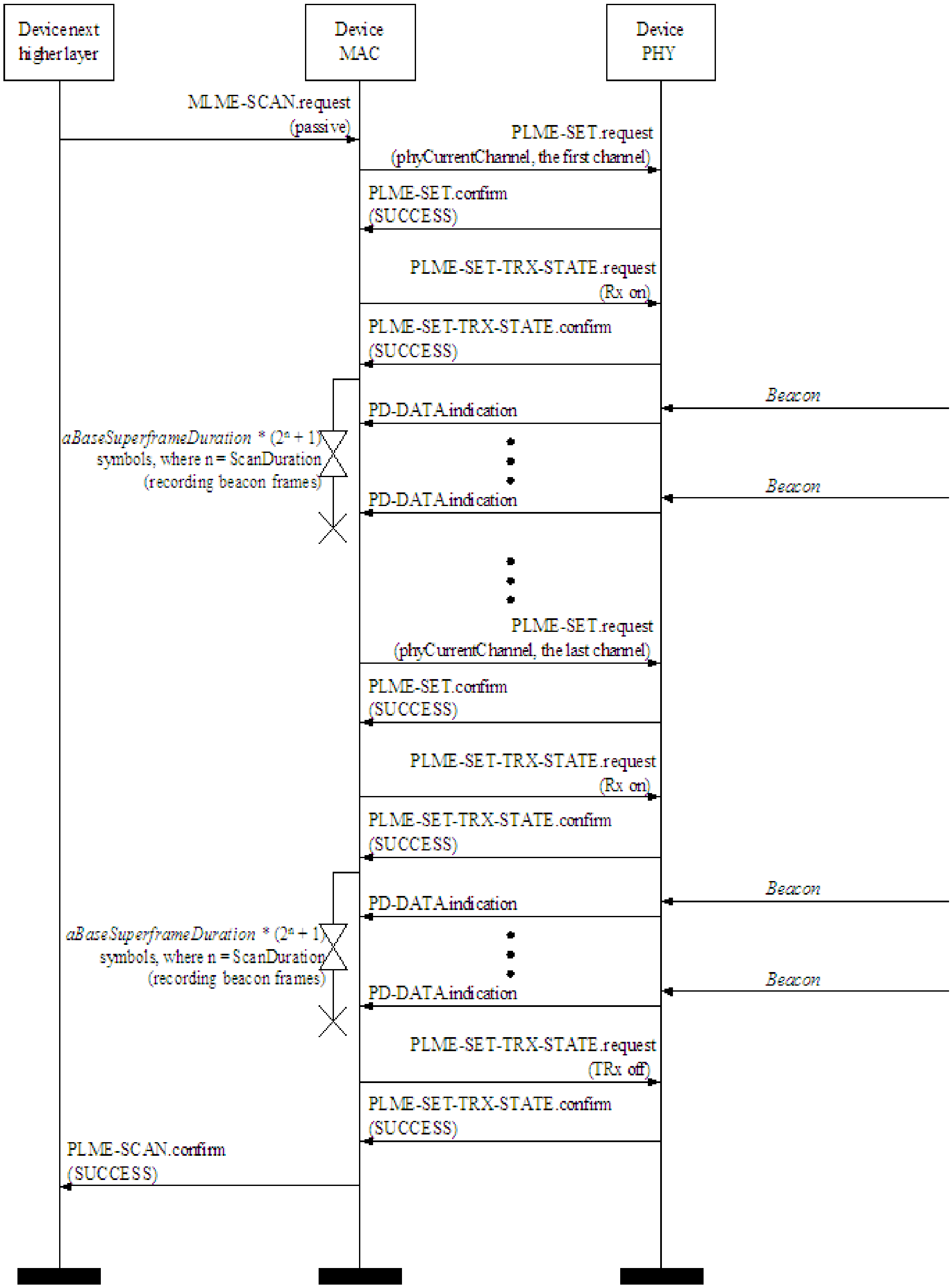


Figure 137—Passive scan message sequence chart

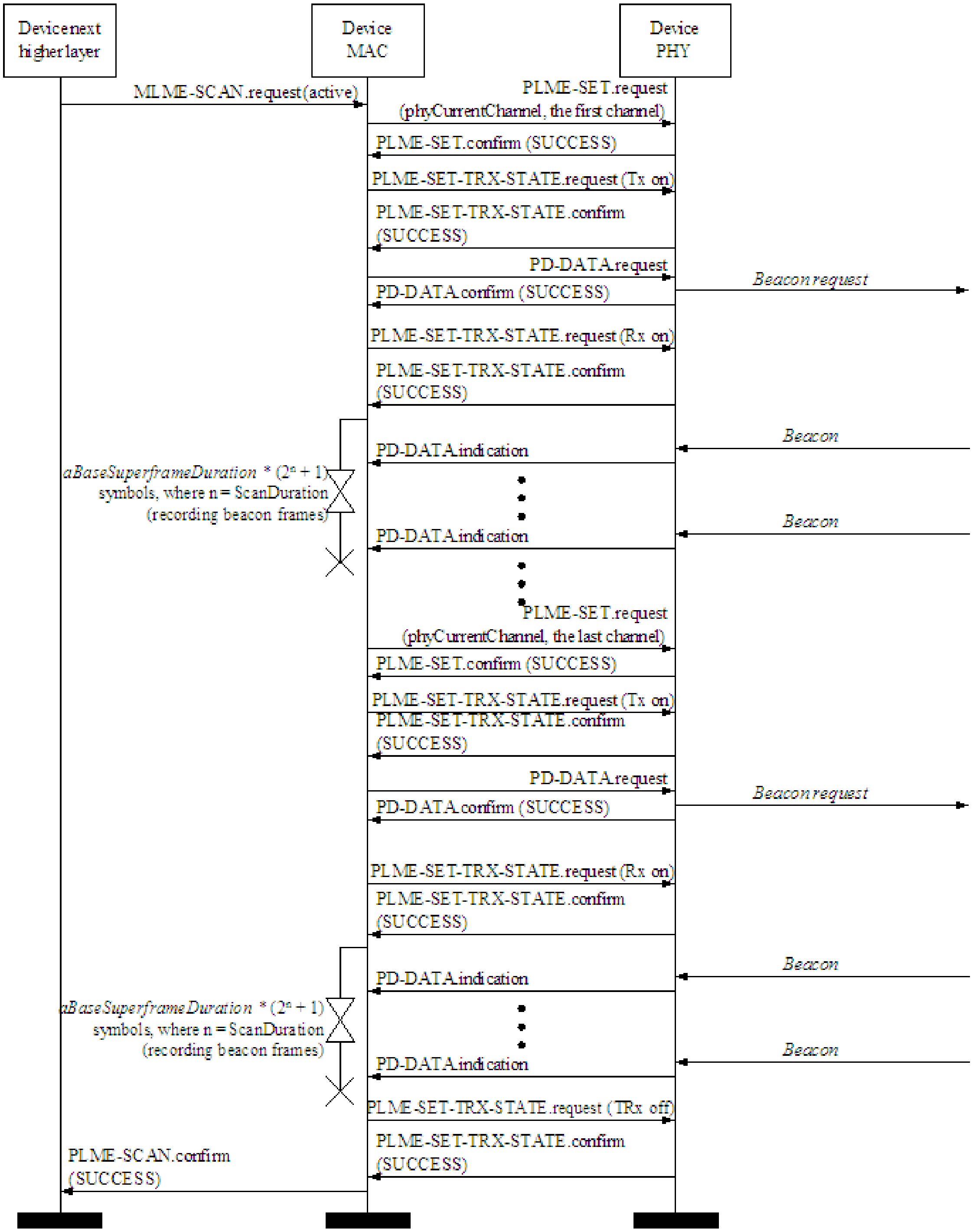


Figure 138—Active scan message sequence chart

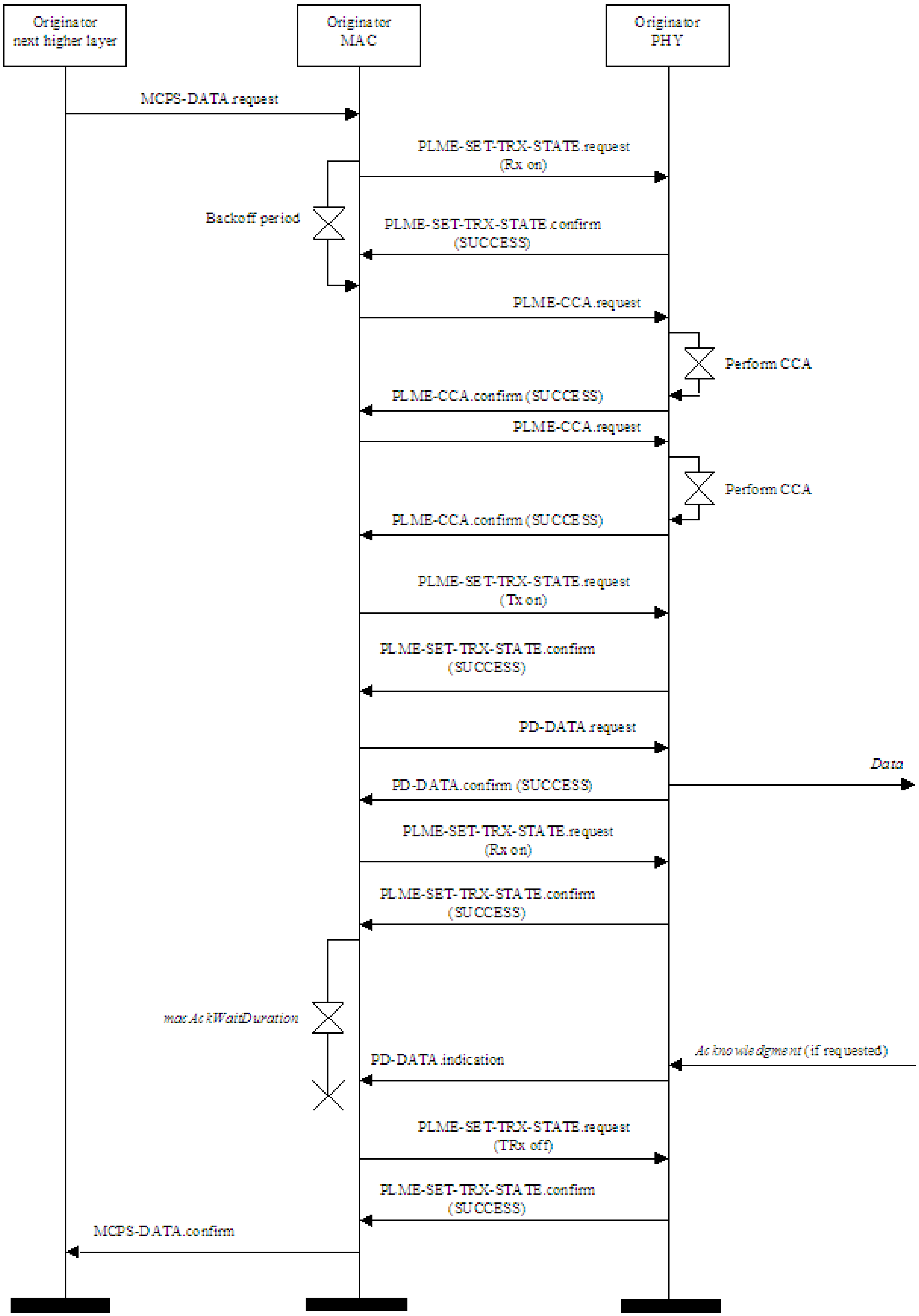


Figure 139—Data transmission message sequence chart—originator

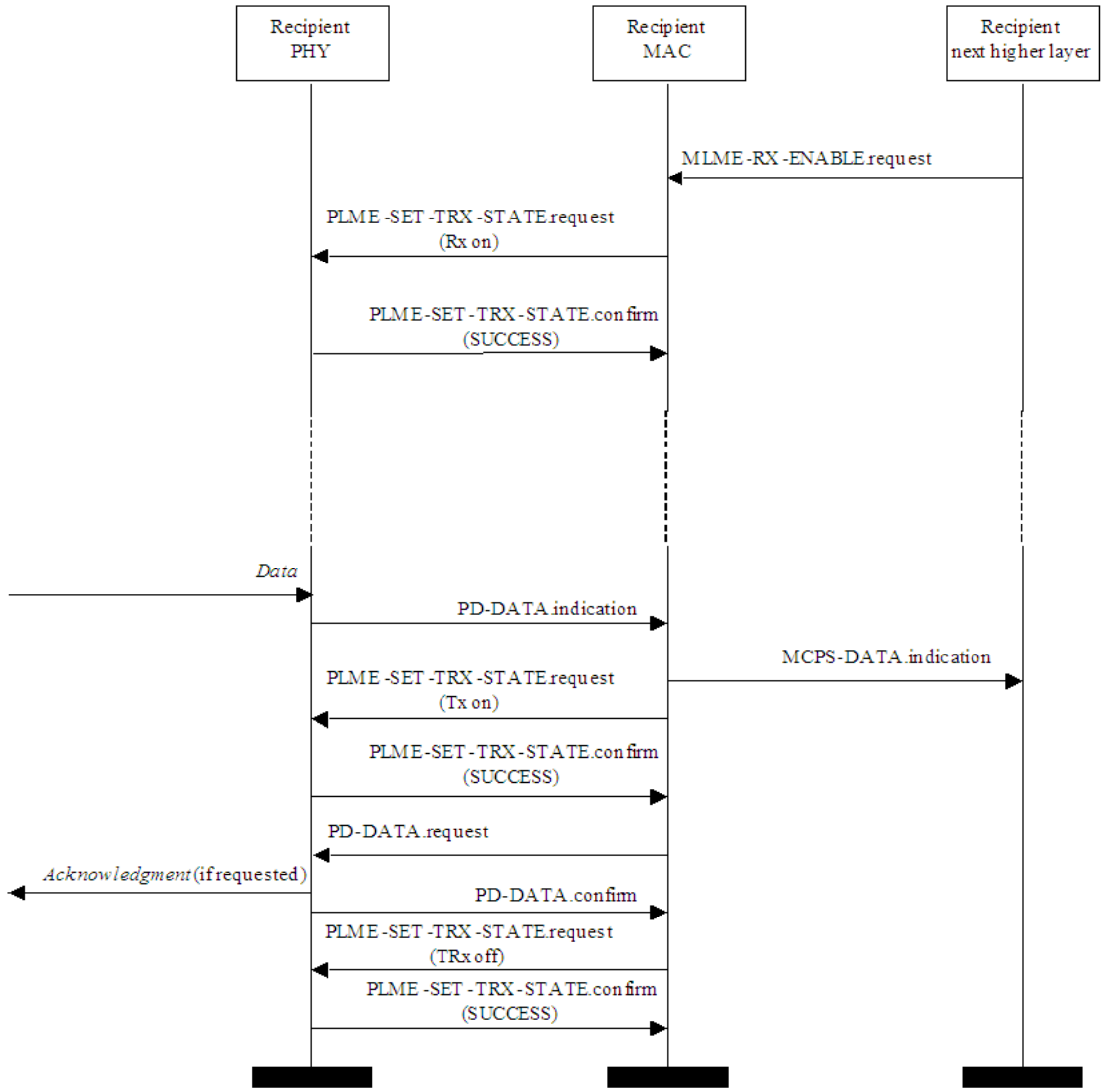


Figure 140—Data transmission message sequence chart—recipient

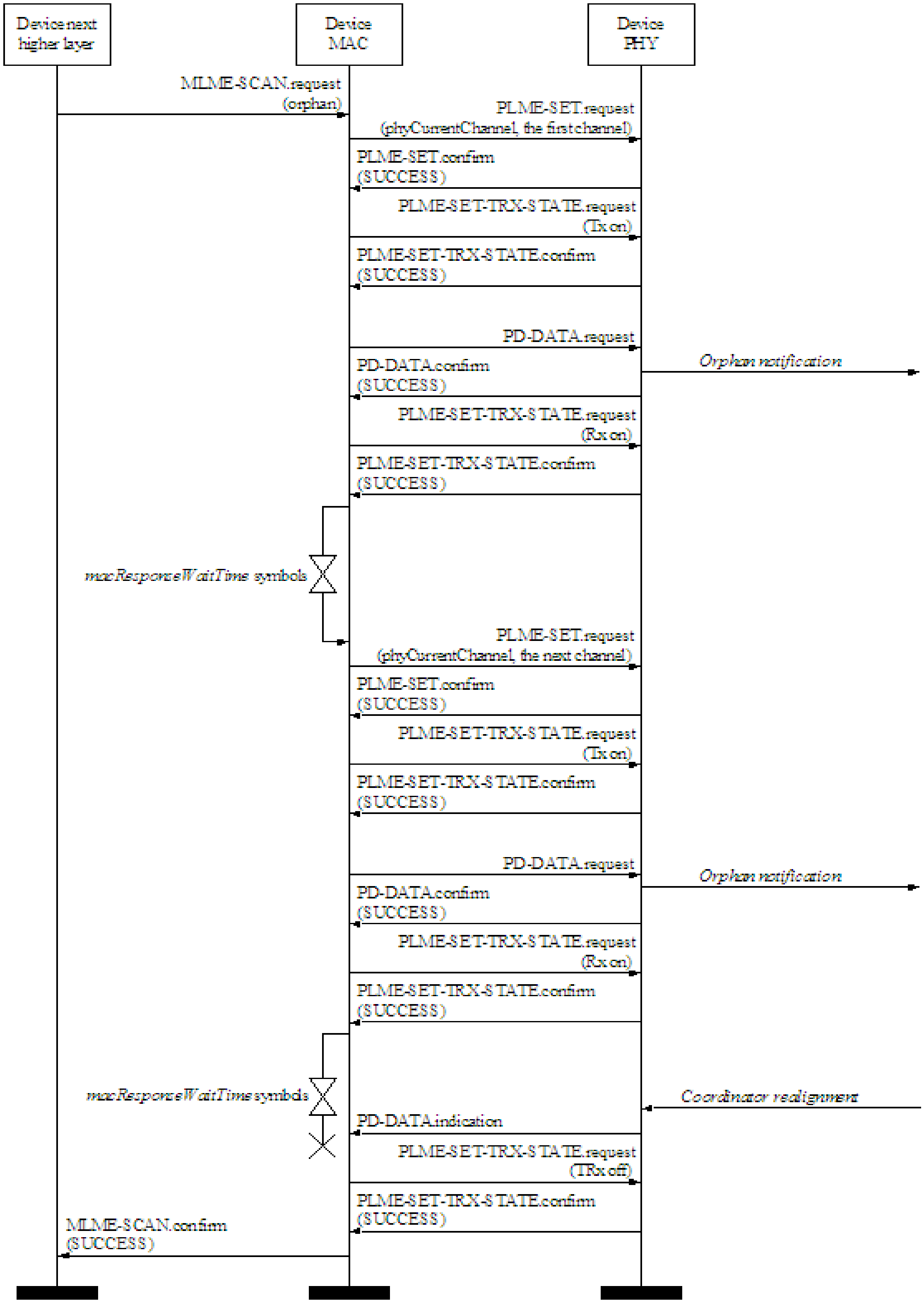


Figure 141—Orphaned device realignment message sequence chart

Annex A

(normative)

Service-specific convergence sublayer (SSCS)

A.1 IEEE 802.2 convergence sublayer

The IEEE 802.2 convergence sublayer exists above the IEEE 802.15.4 MCPS. This sublayer provides an interface between an instance of an IEEE 802.2 LLC sublayer and the IEEE 802.15.4 MCPS.

A.1.1 MA-UNITDATA.request

The MA-UNITDATA.request primitive requests the transfer of a LLC protocol data unit (LPDU) (i.e., MSDU) from a local IEEE 802.2 Type 1 LLC sublayer entity to a single peer IEEE 802.2 Type 1 LLC sublayer entity or multiple peer IEEE 802.2 Type 1 LLC sublayer entities in the case of a group address.

A.1.1.1 Semantics of the service primitive

The semantics of the MA-UNITDATA.request primitive is as follows:

```
MA-UNITDATA.request          (
                             SrcAddr,
                             DstAddr,
                             RoutingInformation,
                             data,
                             priority,
                             ServiceClass
                             )
```

Table A.1 specifies the parameters for the MA-UNITDATA.request primitive.

Table A.1—MA-UNITDATA.request parameters

Name	Type	Valid range	Description
SrcAddr	IEEE address	Any valid IEEE address	The individual IEEE address of the entity from which the MSDU is being transferred.
DstAddr	IEEE address	Any valid IEEE address	The individual IEEE address of the entity to which the MSDU is being transferred.
RoutingInformation	—	null	This parameter is not used by the MAC sublayer and shall be specified as a null value.
data	Set of octets	—	The set of octets forming the MSDU to be transmitted by the MAC sublayer entity.
priority	—	null	This parameter is not used by the MAC sublayer and shall be specified as a null value.
ServiceClass	—	null	This parameter is not used by the MAC sublayer and shall be specified as a null value.

A.1.1.2 Appropriate usage

The MA-UNITDATA.request primitive is generated by a local IEEE 802.2 Type 1 LLC sublayer entity when an LPDU (MSDU) is to be transferred to a peer IEEE 802.2 Type 1 LLC sublayer entity or entities.

A.1.1.3 Effect on receipt

On receipt of the MA-UNITDATA.request primitive, the MAC sublayer entity shall begin the transmission of the supplied MSDU.

The MAC sublayer first builds an MPDU to transmit from the supplied arguments. The MPDU shall be transmitted using the CSMA-CA algorithm in the contention period of the frame and without requesting a handshake.

If the CSMA-CA algorithm indicates a busy channel, the MAC sublayer shall issue the MA-UNITDATA-STATUS.indication primitive with a status of CHANNEL_ACCESS_FAILURE. If the MPDU was successfully transmitted, the MAC sublayer shall issue the MA-UNITDATA-STATUS.indication primitive with a status of SUCCESS.

A.1.2 MA-UNITDATA.indication

The MA-UNITDATA.indication primitive indicates the transfer of an LPDU (i.e., MSDU) from the MAC sublayer to the local IEEE 802.2 Type 1 LLC sublayer entity.

A.1.2.1 Semantics of the service primitive

The semantics of the MA-UNITDATA.indication primitive is as follows:

```
MA-UNITDATA.indication          (
                                SrcAddr,
                                DstAddr,
                                RoutingInformation,
                                data,
                                ReceptionStatus,
                                priority,
                                ServiceClass
                                )
```

Table A.2 specifies the parameters for the MA-UNITDATA.indication primitive.

A.1.2.2 When generated

On receipt of a data packet at the local MAC sublayer entity, the FCS field is checked. If it is valid, the MAC sublayer shall issue the MA-UNITDATA.indication primitive to the IEEE 802.2 Type 1 LLC sublayer entity, indicating the arrival of a MSDU. If the FCS is not valid, the packet shall be discarded, and the IEEE 802.2 Type 1 LLC sublayer entity shall not be informed.

A.1.2.3 Appropriate usage

The appropriate usage of the MA-UNITDATA.indication primitive by the IEEE 802.2 Type 1 LLC sublayer entity is not specified in this standard.

Table A.2—MA-UNITDATA.indication parameters

Name	Type	Valid range	Description
SrcAddr	IEEE address	Any valid IEEE address	The individual IEEE address of the entity from which the MSDU has been received
DstAddr	IEEE address	Any valid IEEE address	The individual IEEE address of the entity to which the MSDU is being transferred.
RoutingInformation	—	null	This parameter is not used by the MAC sublayer and shall be specified as a null value.
data	Set of octets	—	The set of octets forming the MSDU received by the MAC sublayer entity.
ReceptionStatus	—	null	This parameter is not used by the MAC sublayer and shall be specified as a null value.
priority	—	null	This parameter is not used by the MAC sublayer and shall be specified as a null value.
ServiceClass	—	null	This parameter is not used by the MAC sublayer and shall be specified as a null value.

A.1.3 MA-UNITDATA-STATUS.indication

The MA-UNITDATA-STATUS.indication primitive reports the results of a request to transfer a LPDU (MSDU) from a local IEEE 802.2 Type 1 LLC sublayer entity to a single peer IEEE 802.2 Type 1 LLC sublayer entity or to multiple peer IEEE 802.2 Type 1 LLC sublayer entities.

A.1.3.1 Semantics of the service primitive

The semantics of the MA-UNITDATA-STATUS.indication primitive is as follows:

```
MA-UNITDATA-STATUS.indication    (
                                 SrcAddr,
                                 DstAddr,
                                 status,
                                 ProvPriority,
                                 ProvServiceClass
                                 )
```

Table A.3 specifies the parameters for the MA-UNITDATA-STATUS.indication primitive.

A.1.3.2 When generated

The MA-UNITDATA-STATUS.indication primitive is generated by the MAC sublayer entity in response to an MA-UNITDATA.request primitive issued by the IEEE 802.2 Type 1 LLC sublayer.

A.1.3.3 Appropriate usage

The receipt of the MA-UNITDATA-STATUS.indication primitive by the IEEE 802.2 Type 1 LLC sublayer entity signals the completion of the current data transmission.

Table A.3—MA-UNITDATA-STATUS.indication parameters

Name	Type	Valid Range	Description
SrcAddr	IEEE address	Any valid IEEE address	The individual IEEE address of the entity from which the MSDU has been transferred.
DstAddr	IEEE address	Any valid IEEE address	The individual IEEE address of the entity to which the MSDU has been transferred.
status	Enumeration	SUCCESS, TRANSMISSION_PENDING, NO_BEACON, or CHANNEL_ACCESS_FAILURE	The status of the last MSDU transmission.
ProvPriority	—	null	This parameter is not used by the MAC sublayer and shall be specified as a null value.
ProvServiceClass	—	null	This parameter is not used by the MAC sublayer and shall be specified as a null value.

Annex B(informative) VLC Topologies, Applications and Modes

VLC provide many applications such as LED illumination, Broadcasting, and Machine-to-machine. LED illumination can be an office/home illumination, streetlight, and vehicle lamp. Broadcasting can be a signboard, an office/home illumination, and a streetlight. Machine-to-machine can be a cellular phone to a cellular phone, a vehicle to a vehicle, a vehicle to a traffic signal, and a vehicle to a streetlight.

B.1 P2P (Peer-to-peer)

Usually, P2P VLC application implies communications between two VLC devices. Each device can support single light source and single PD. P2P can support high data rate and relatively short communication distance.

B.2 IB (Information Broadcasting)

The IB VLC system is for example LED signboard that is used for advertising, noticing and etc with additional information which is transferred through the light. An arrayed light source can be used.

B.3 Visible LAN

Visible LAN is some kinds of LAN (Local Area Network) service using the visible light. Each light bulb or arrayed light source would act as an access point.

B.4 VB(Vehicle Broadcasting)

Vehicle broadcasting is for car to car or infrastructure to car communication.

VLC can make a lot of applications. To support all kind of application, VLC PHY and MAC should support different scheme according to application requirement.

B.5 VLC application and mode

The categorized VLC application mode and other brief characteristics of VLC systems are summarized in table 1.

Application mode	P2P	VLAN / IB / VB	VLAN
Beacon mode	Non beacon	Beacon	
Link	Downlink/Uplink	Downlink	Uplink
Frame slot	Non slot	Slot	
Frame type	Data Visibility Management Ack	Data Visibility Management Beacon Ack	

Table 90—VLC Application Mode

There are several VLC application mode, like P2P, star topology, IB and VB, that can be categorized into beacon and non-beacon mode. IB and VB application mode support only unidirectional communication. Frame slot is used only in beacon mode. Several frame types are used in VLC.

Beacon signal is used to indicate start of frame and define number of slots to be allocated for contention, uplink and downlink. Non-beacon mode is used only for the P2P application mode.

Annex CColor Channel Tolerance

VLC is needed a different scheme in terms of color communication. We have to consider color channel tolerance of receiver sensitivity at receiver side. There are receiver requirements for VLC applications using color channels. Color channel tolerance is considered according to sources and mechanism of color channel difference in receiver sensitivity.

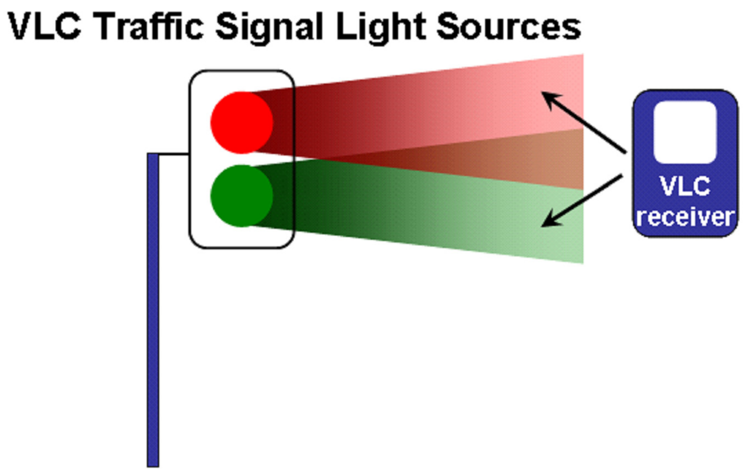


Figure 01—A case of VLC application using color channels: single color at one snap time

There are various VLC scenarios using many color channels.

Single color at one time

Single color at one lamp

Multiple color at one lamp

In case of single color at one time, a receiver receives only one color.

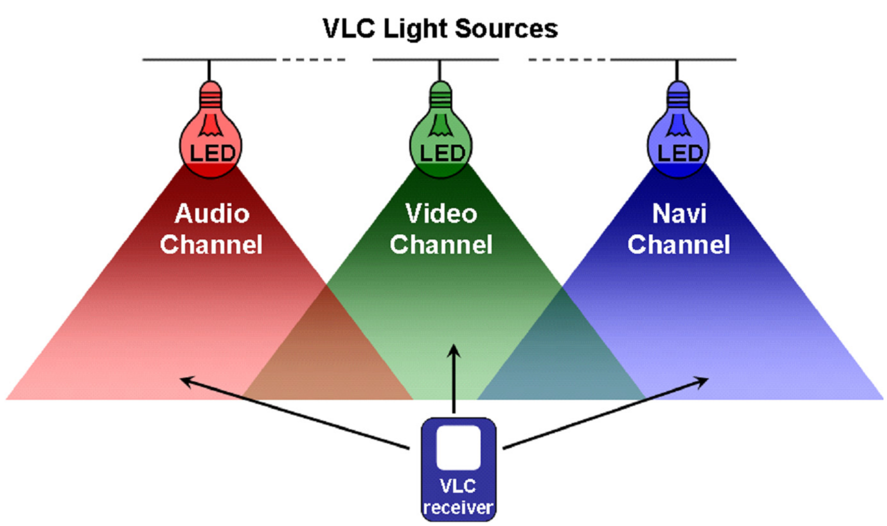


Figure 02—A case of VLC Application using Color Channels: single color of a lamp

In case of single color from one lamp, a receiver receives several colors from different lamps. A VLC receiver supports every color channels. When audio, video, and navigation services are given by the respective R, G, B channels.

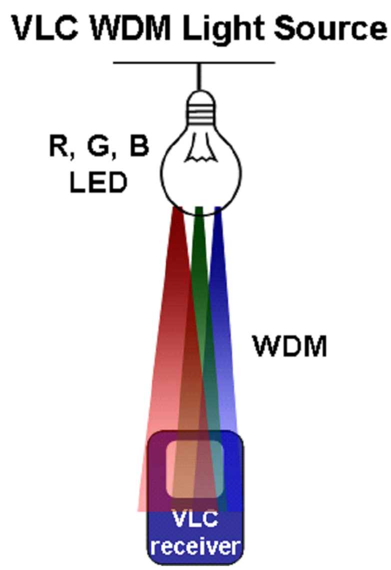


Figure 03—A case of VLC Application using Color Channels: multiple colors of a lamp

In case of multiple colors from one lamp, a receiver has to support a WDM technology as well as multiple color receiving capability.

There are basic receiver requirements for VLC applications using color channels.

The first thing is A VLC receiver must support the various color channels according to VLC band plan when we use the various color channels.

The second thing is A VLC receiver must have constant receiver sensitivities in a tolerance range for the respective color channels because it will be in trouble if a VLC receiver operates well on a certain color channel but it do not operates on another color channel.

The color channel tolerance of receiver sensitivity is needed for a better communication. We need to know the sources of color channel differences in receiver sensitivity for the color channel tolerance. These are the sources of color channel differences in receiver sensitivity. Of course, besides this source, other things can make the color channel differences. VLC using color channels basically has the color channel difference because of the relation between the radiometric and photometric units. VLC transmitters using various color channels has so different light powers (Watt) at respective color channel even under the same conditions because even under the VLC environment, human eye have to feels that each VLC color channel source emit each color light at the same brightness. The same condition means the same brightness and divergence angle at the same distance. A green color channel has less radiant flux (Watt) than a red or blue channel at the same brightness (lumen).

Most of Si-photo detectors show different sensitivities depending on the visible wavelength region.

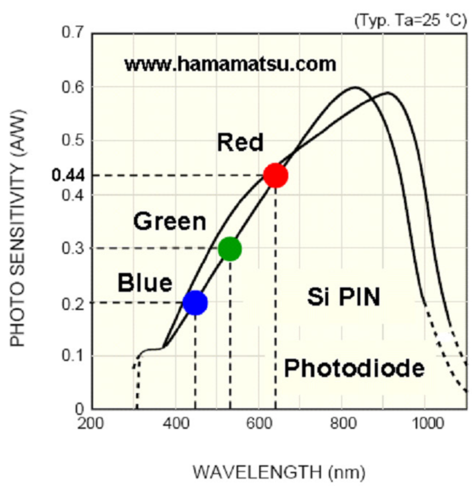
Table A4—Calculated Color Channel Difference Table at Receiver Input

Wavelength Band (nm)		Center Wavelength (nm)	V(λ) at C.W.	Receiver input power (Watt) @1 lm
380	400	390	0.0008	1.8302
400	500	450	0.0468	0.0313
500	560	530	0.8620	0.0017
560	620	590	0.7570	0.0019
620	660	640	0.1750	0.0084
660	720	690	0.0082	0.1786
720	780	750	0.0001	14.6413

V(λ) : Human eye sensitivity function, C.W. : Center Wavelength
Ref. : E. Fred Schubert, *Light-Emitting Diodes.* Cambridge University Press, 2003.

This table is calculated table showing how much receiver input power difference for each color channel happens when we consider.

V lambda is relative eye sensitivity function at center wavelength. For simple calculation, we calculated the receiver input power for only each center frequency. Here we suppose 1 lumen enter into the receiver.



Center Wavelength (nm)	Receiver input power (Watt) @1 lm	PD output current (mA) @1 lm
450	0.0313	6.3
530	0.0017	0.5
640	0.0084	3.7

Figure A1—Calculated Color Difference Table at Photo detector Output

This table is calculated table showing how much receiver output current difference for each color channel after O/E (Optical to Electronic) power conversion happens when we consider both the photometry to radiometry conversion and the wavelength dependence on photo diode (PD).

Calculation was done only three R, G, B color channels. VLC using color channels basically has the color channel difference in receiver sensitivity because of the relation between the radiometric and photometric units and the wavelength dependence of a VLC receiver. We propose we need to make the concept of the color channel tolerance of receiver sensitivity.

We propose that we, VLC, determine the Color channel tolerance receiver sensitivity in VLC using color channels as plus minus 5 % of receiver sensitivity mean value. Receiver sensitivity mean value means the average values of receiver sensitivities for each color channel.