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Wireless Personal Area Networks

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Re:	
Abstract	This document proposes IEEE 802.15.7 VLC PHY/MAC Specification.
Purpose	[This document is intent to propose TG7 specification.]
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IEEE 802.15.7 VLC PHY/MAC Specification

Note to TG7 editor:

- This document represents merged text that is supported by listed members from Samsung and ETRI
- This document uses IEEE 802.15.4 standard as the basic reference for the MAC and makes several modifications for VLC support. We would refer the editor to consider the IEEE 802.15.4 standard for details on items that have been excluded from this document such as security, for example.
- We are continuing work to improve the document and also seeking support from other members in TG7.
- We hope this merged document minimizes the workload on your end to integrate the proposals. We look forward to assisting you in your editing work.

Note to TG7 committee members:

- We have made some modifications to the proposal over what was presented in the last IEEE meeting based on the feedback received from the committee. We have attempted to explain many of the changes made via TG7 conference calls. There may have been some changes that we may not have had time to explain in the committee earlier. Kindly look over the proposal and let us know if any items need further explanation.

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1. Definitions

FFS

2. 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

3. General description

Visible Light Communication is a new communication system that uses the visible light for communication. Several optical sources such as LED/LD can be used as a light source. The data can be transmitted by switching the light on and off very fast so that the flicker cannot be recognized by the human naked eyes.

By using the visible light for the data communication, many of the radio and infrared wavelength problems can be solved. Some of the general advantages of VLC as follow:

- Safe for human
- Avoid a radio wave restriction
- Using at the RF restricted area, like hospital, airplane and etc.

Some of the characteristic of VLC system in this standard as follow:

- Over-the-air data rates of 160Kbps ~ 96Mbps (uncoded data rate)
- Several different modes (Peer to Peer, Information Broadcasting, Visible LAN, and Vehicle Broadcasting)

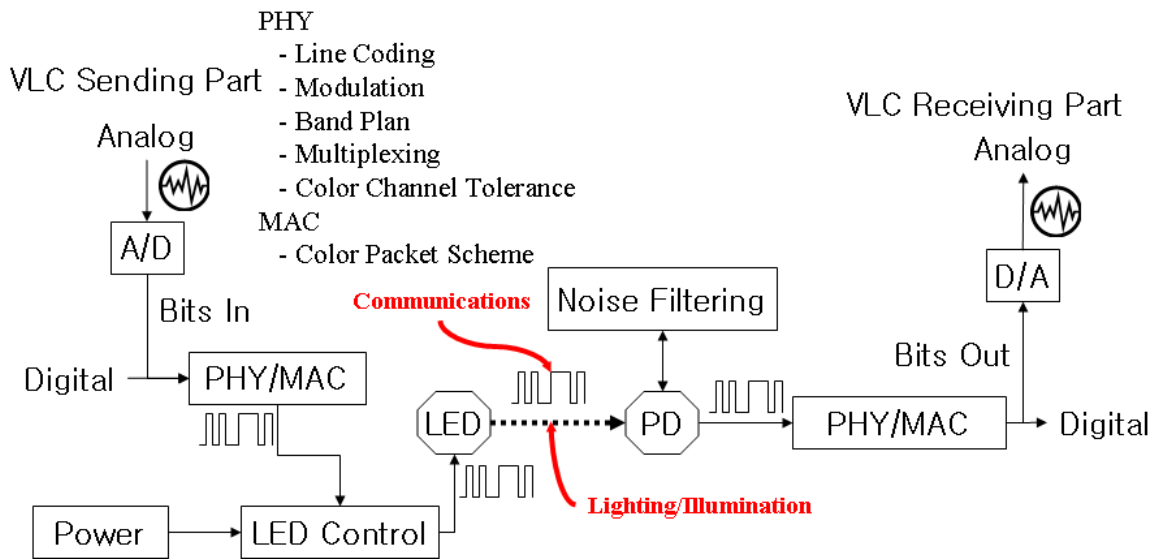
VLC (Visible Light Communications) provides a merged function from two different areas:

LED Lighting and Communications. LED Lighting Communications can provide new communication with LED applications such like lighting, signboard, streetlight, vehicle, and traffic signal. VLC provides new functions with color lighting wireless communications. Unfortunately, VLC can also make side effects of LED illumination such as a flickering, restricted dimming, and effect of illumination Pulse Width Modulation (PWM). There is no defined standard for an LED interface and a VLC interface.

3.1. VLC Architecture

There are two part of VLC Architecture. One is a sending part of VLC. The other is a receiving part. The sending part can use any kind of LED illumination. The sending part of VLC MUST have PHY/MAC functions for illumination and transmission performance.

The receiving Part of VLC can support any kind of Photo Diode (PD) with avoidance from any other light interference. As a common part of two parts, there are a PHY and a MAC of VLC. VLC PHY has a modulation and a line coding for a wireless communication. VLC MAC has to support different Applications.



(Figure 1) VLC PHY Architecture with Lighting

3.2. VLC Applications

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.

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.

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.

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.

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.

LED illumination with VLC MUST support as followings;

- Dimming Control Scheme
- Flicker Removal Scheme
- Full Brightness Scheme

Broadcasting with VLC MUST support as followings;

- TDM: Signboard

Machine-to-machine with VLC MUST support as followings;

- Color Packet according to PER

3.3. VLC Network topologies

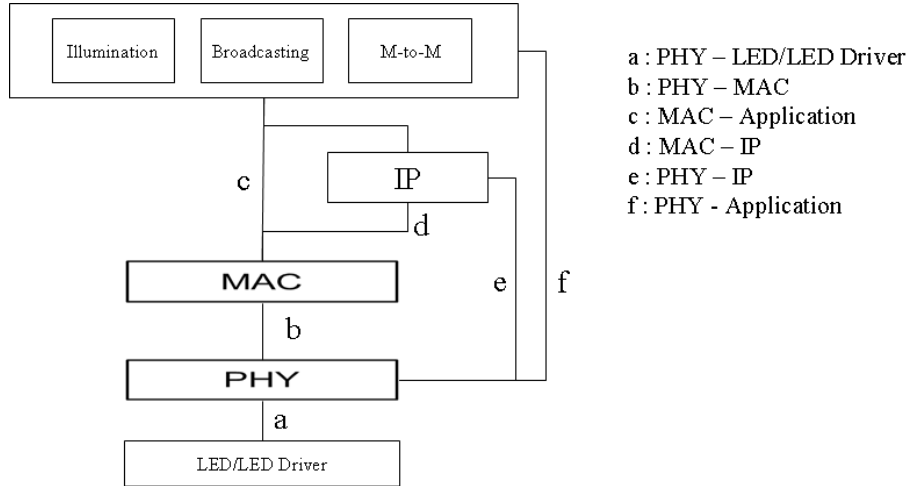
VLC can support two different network topologies: star network and peer-to-peer network. Star network provides information from one lighting source to one more different receiving destination. The one light source can be an LED lighting/illumination or a sign board for broadcasting data transfers.

Peer-to-peer network can provide from one lighting source to one receiving destination. This is

similar to a kind of machine to machine for peer-to-peer data transfers.

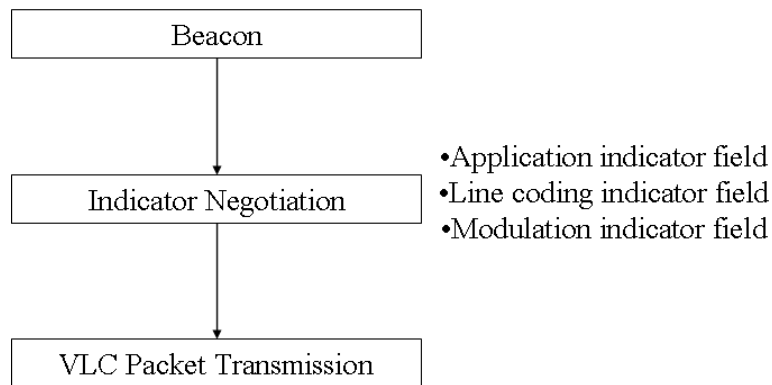
3.4. VLC Interfaces on Protocol Stack

The VLC specification supports illumination, broadcasting, and M-to-M.



(Figure 2) VLC Interfaces on Protocol Stack

3.5. Application Selection Procedure



(Figure 3) VLC Setup Procedure

(Table 1) Indicator Negotiation format

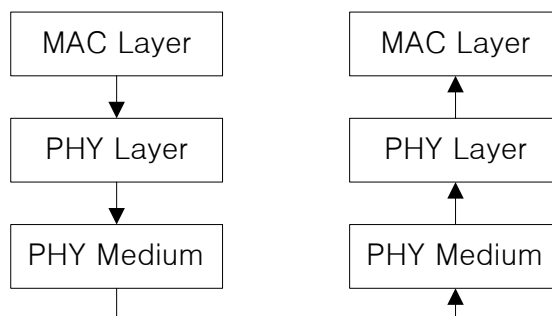
Application indicator field	
0001	Lighting (illumination)
0010	Signboard
0011	Machine-to-machine

0100 - 1111	Reserved
Line coding indicator field	
0001	Modified 4B5B
0010	4B6B
0011	8B10B
0100 - 1111	Reserved
Modulation indicator field	
0001	OOK
0010	VPM
0011	R-RZ
0100 - 1111	Reserved

3.6. Components of the IEEE 802.15.7 WPAN

A system conforming to this standard consists of several components. The most basic device may consist of transmitter and receiver. This system shall include at least one optical light source and one optical receiver photo-detector as transmitter and receiver respectively.

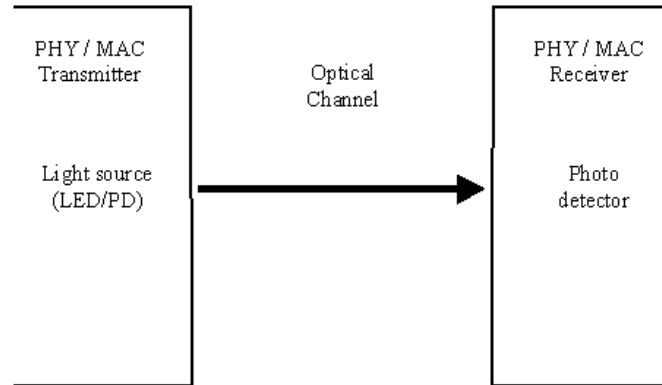
4. Architecture



(Figure 4) Architecture

The IEEE 802.15.7 architecture is defined as a several number of blocks to simplify the standard. These blocks are called layers in Figure 1. Each layer is responsible for one part of the standard and offers services to the higher layers. The higher layers are not described and outside the scope in this standard.

Figure 2 shows the basic model of VLC transmitter and receiver. In wireless optical communication link, VLC transmitter can have an optical source such as LED (Light Emitting Diode) / LD (Laser Diode) for transmission part and receiver can receive data with optical receiver such as a PD (Photo Detector).



(Figure 5) VLC transmitter and receiver

4.1. MAC and PHY layers

4.1.1. Physical layer (PHY)

The Physical Layer defines the electrical and physical specifications for devices. In particular, it defines the relationship between a device and a physical medium. One device transmits data to the medium, and another device receives data from medium based on the physical layer.

The functions and services of the Physical Layer are link establishment and termination of a connection to a communications medium.

4.1.2. MAC sub layer

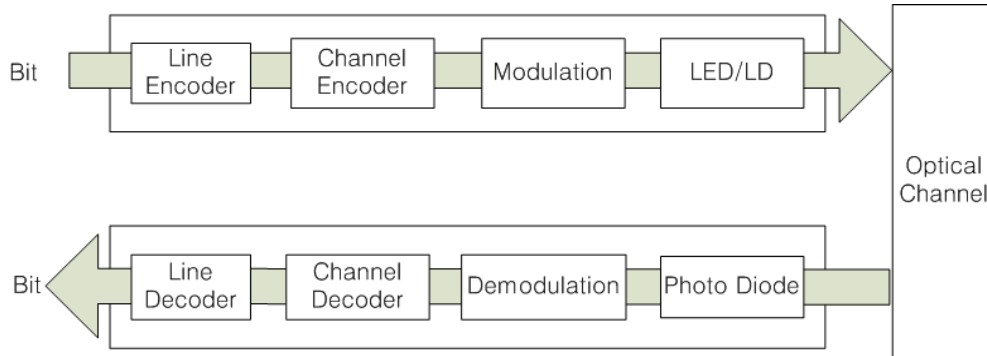
The Media Access Control (MAC) data communication protocol sub-layer provides addressing and channel access control mechanisms that make it possible for several terminals or devices. The hardware that implements the MAC is referred to as a Medium Access Controller. This channel may provide unicast, multicast or broadcast communication service.

4.2. Functional overview

4.2.1. Block Diagram

Figure 3 describes the general block diagram of normal VLC system consists of two parts; VLC transmit module and receive module. At the transmit module, the encoded data by the encoder is transformed to optical signal and that optical signal is transmitted by the light source using driver to the receive module.

The signal is detected, changed into the electric signal by detector and amplified. Finally, the data can be acquired through the decoder.



(Figure 6) Block Diagram

4.2.2. VLC application and mode

The categorized VLC application mode and other brief characteristics of VLC systems are summarized in table 1.

(Table 2) VLC Application Mode

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	

There are several VLC application mode, like P2P, VLAN, 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.

4.2.2.1. Beacon/Non beacon mode

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.

4.2.2.2. Frame structure

4.2.2.3. Data frame

Figure 4 shows the structure of the data frame, which originates from the upper layers. A data frame is used to transfer the data in all modes. There are Single, Packed and Burst types. Detail information will be provided in chapter 6 and 7.



(Figure 7) Data Frame

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).

4.2.2.4. Visible/Dimming frame

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



(Figure 8) 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.

4.2.2.5. Acknowledgment frame

Acknowledgement frame is used for ACKs in VLAN and P2P mode.

4.2.2.6. Management frame



(Figure 9) Management Frame

Used in all modes for association, security, power and etc.

4.2.2.7. Beacon Frame



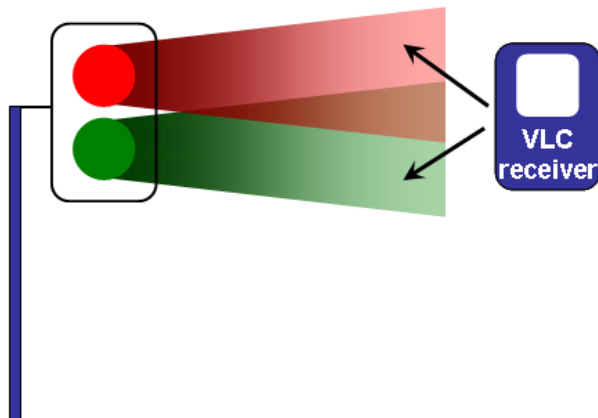
(Figure 10) Beacon frame

Beacon frame is used in VLAN and IB/VB modes. Detail information will be provided in chapter 6 and 7.

4.3. Color 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.

VLC Traffic Signal Light Sources

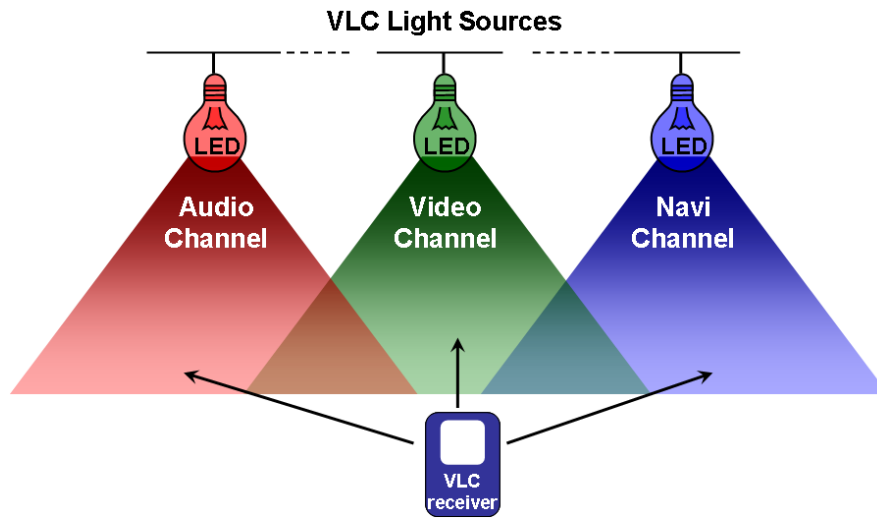


(Figure 11) A case of VLC Application using Color Channels: single color at one snap time

There are various VLC scenarios using many color channels.

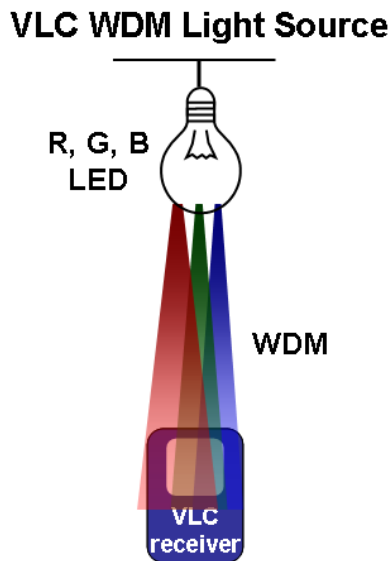
- Single color at one time
- Single color at one lamp
- Multiple color at one lamp

In case of single color at one time, a receiver receives only one color.



(Figure 12) 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 13) 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.

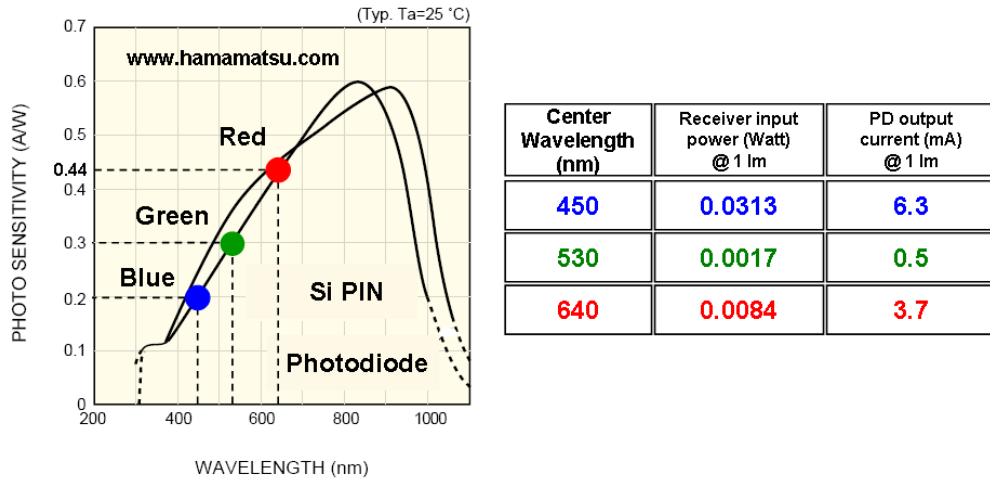
(Table 3) Calculated Color Channel Difference Table @ Receiver Input

Wavelength Band (nm)		Center Wavelength (nm)	$V(\lambda)$ 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

$V(\lambda)$: 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.



(Figure 14) Calculated Color Channel Difference Table @ 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 PIN receiver sensitivities for each color channel.

4.4. Regulations

There are two eye/skin safety issues related to regulation.

- Visible light flickering
- Visible light strength

The PHY modulation of Visible Light Communication can make light flickering. The light flicker can have harmful health impacts on humans/animals.

A light 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 [Wikipedia].

A light flicker causes 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], Photosensitive epilepsy (2% of all epilepsy cases) [Harding, 1995].

Requirement: Even though low-bit-rate transmission or bunching data, the modulation frequency of VLC MUST be higher than CFF (critical fusion frequency) threshold.

The CFF (critical fusion frequency) threshold is:

- The 1/minimum flickering frequency is 200 Hz (= 5ms).
- Brightness of each Maximum Flickering Time Period (MFTP) must be all equal

5. PHY specification

5.1. PHY layer characteristics

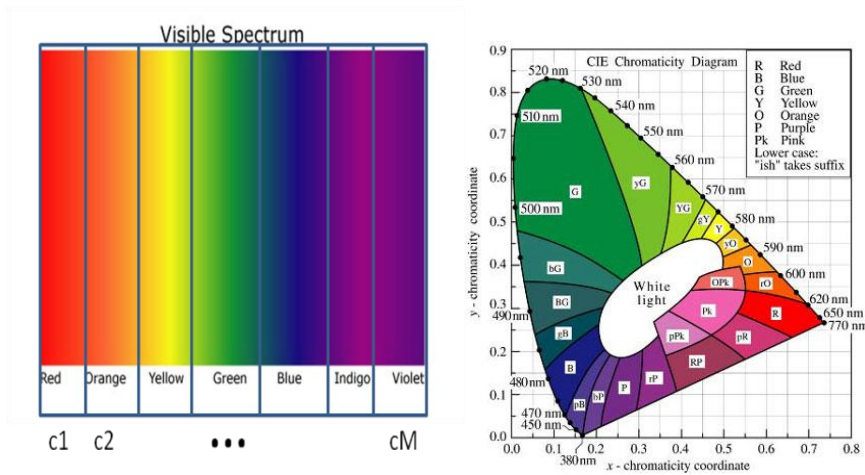
5.1.1. Operating wavelength range

The visible light spectrum defined in this standard is from minimum 380 nm to maximum 780 nm in wavelength.

5.1.2. Channel assignments

- Center colors are narrower in width than outer colors.
- Human eye is more sensitive to center colors
- pB, R occupy 100~200 nm while G occupies ~ 30 nm
- LED manufacturers make LEDs depending on human color perception and not frequency band

=> Non-linear widths needed for band plan



(Figure 15) Visible spectrum and chromaticity coordinate

5.1.2.1. Band plan for visible light communication

The VLC standard provides support for 7 bands in the visible light spectrum. The bands proposed take the non-linear color sensitivity of the human eye and the corresponding LED spectral widths from different manufacturers into account.

(Table 4) VLC channel numbering

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, Y,yO,O	011
600 - 650	50	rO	100
650 - 710	60	R	101
710 - 780	70	R	110
		Reserved	111

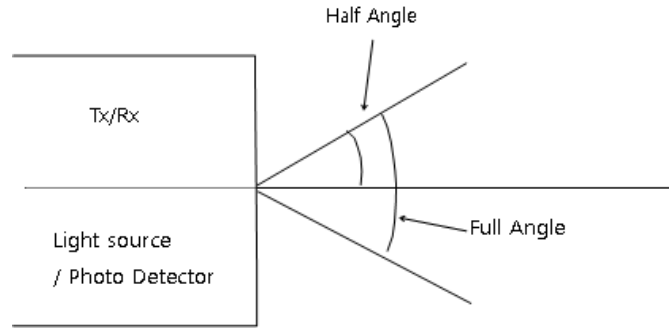
5.1.3. Transmit power

The maximum transmit power shall conform to local regulations.

5.1.4. Optical angle

The optical axis is assumed to be normal to the surface of the device’s face that contains the optical port.

- Transmitter: Divergence angle
- Receiver: FOV (Field of View)



(Figure 16) Optical Angle

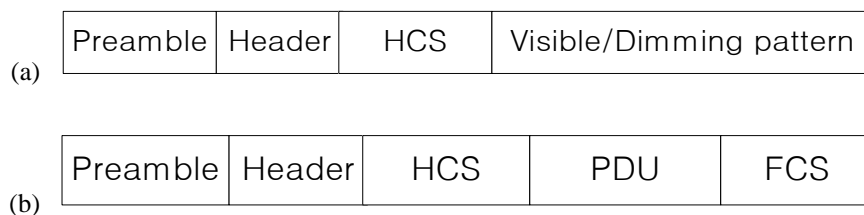
The data rate performance of the VLC system depends on transmitting and receiving signal angle. It is called the divergence angle and the field of view, respectively. These divergence angle and field of view can be controlled by mechanical setting or manual setting for keeping the good link status.

To increase the data rate, usually the smaller divergence angle and the wider field of view are desirable.

5.2. PPDU format

This sub 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 sub layer.



(Figure 17) Frame formats (a) Visibility frame (b) all other frames

5.2.1. Preamble field

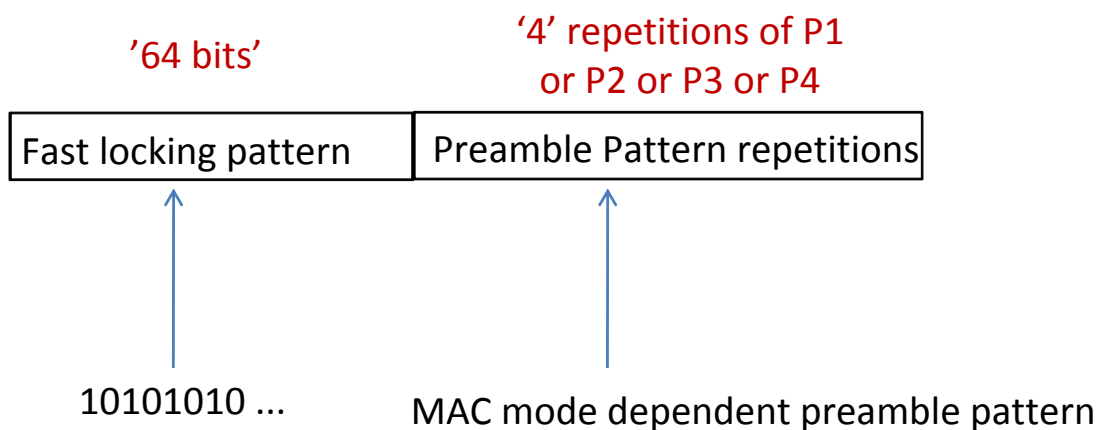
The standard defines one fast locking pattern followed by choice of 4 preambles for the purposes of distinguishing different modes of MAC operation such as IB, VB, P2P and VLAN.

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.

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 the four preambles P1, ... , P4 are sent.

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 18) Proposed preambles for various application modes



(Figure 19) Default preamble transmission

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 5) Preamble for MAC operation code

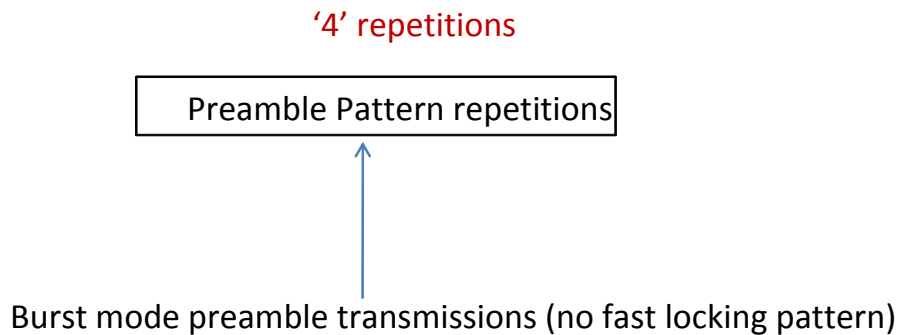
Preamble	MAC operating mode
P1, ~P1	P2P
P2, ~P2	VLAN
P3, ~P3	IB
P4, ~P4	VB

The same preamble sequences are used for low rate and high rate PHY. The preamble is sampled at the lowest sampling frequencies supported by the 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.

5.2.1.1. 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 20) Burst preamble transmission

5.2.2. PHY Header

(Table 6) 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	8	PHY data rate
Length of MAC payload	16	Length up to 64KB
Reserved fields	4	For future extension

The header SHALL be transmitted with an OOK modulation. If there are multiple light sources supported 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.

5.2.3. 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.

5.2.4. 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: $x^{16} + x^{12} + x^5 + 1$. 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.

5.2.5. 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 21) 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.

• Visibility patterns: V_0, V_1, \dots, V_K ($V_0 = 0\%$, $V_K = 100\%$)

• Desired visibility = dv (percentage)

• Desired precision = p , $p \leq 0$, $p \in \mathbb{Z}$

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} reppat1times

repeat V_{sel2pat} reppat2times

(Figure 22) Generating high resolution visibility patterns

5.3. Low and High data rate PHY specifications

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 160 Kbps to 96Mbps in uncoded data rate.

(Table 7) Data rates of high and low PHY

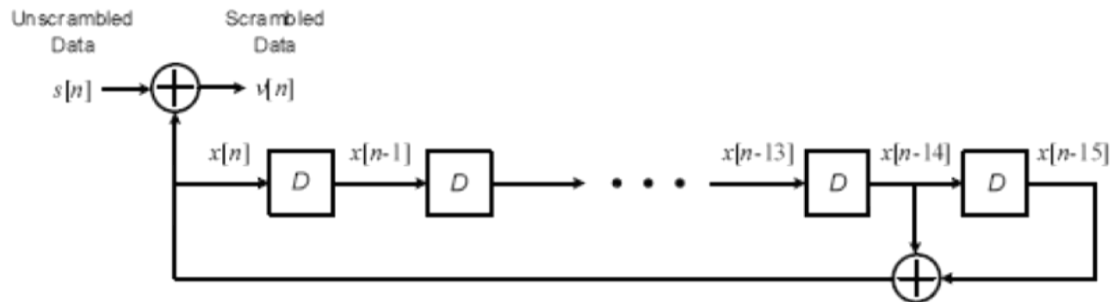
Channel Coding	Line coding	Sampling frequency	Uncoded data rate
2/3	4/5	300K	160 kbps
1	2/3	300K	200 kbps
2/3	4/5	600K	320 kbps
1	2/3	600K	400 kbps
2/3	4/5	900K	480 kbps
1	2/3	900K	600 kbps
2/3	4/5	3M	1.6Mbps
1	2/3	3M	2.0Mbps
2/3	4/5	6M	3.2Mbps
1	2/3	6M	4.0Mbps
2/3	4/5	9M	4.8Mbps
1	2/3	9M	6.0Mbps
2/3	4/5	12M	6.4 Mbps
1	4/5	12M	9.6 Mbps
2/3	4/5	48M	25.6 Mbps
1	4/5	48M	38.4 Mbps
2/3	4/5	96M	51.2 Mbps
1	4/5	96M	76.8 Mbps
2/3	4/5	120M	64 Mbps
1	4/5	120M	96 Mbps

5.4. Scrambling

Scrambling is used to support coding schemes such as CCM and HHW where a line code cannot be used as it destroys the properties of the code. Using a scrambler as an input ensures pseudo-random data for VLC. All input to the VLC system shall be scrambled.

The polynomial generator, $g(D)$, for the pseudo-random binary sequence (PRBS) generator shall be: $g(D) = 1 + D^{14} + D^{15}$, where D is a single bit delay element.

Using this generator polynomial, the corresponding PRBS, $x[n]$, is generated as $x[n] = x[n-14] \oplus x[n-15]$, $n = 0, 1, 2, \dots$ where " \oplus " denotes modulo-2 addition.



(Figure 23) Proposed scrambler

The side-stream de-scrambler at the receiver shall be initialized with the same initialization vector, x_{init} , used in the transmitter scrambler. The initialization vector is determined from the seed identifier contained in the PLCP header of the received frame.

The 15-bit initialization vector or seed value shall correspond to the seed identifier as defined in Table. The MAC shall set the seed identifier value to 00 when the PHY is initialized and this value shall be incremented in a 2-bit rollover counter for *each* frame sent by the PHY.

(Table 8) Scrambler Seed Selection

Seed Identifier (S1, S2)	Seed Value $x_{init} = x_{i[-1]} x_{i[-2]} \dots x_{i[-15]}$	PRBS Output First 16 bits $x[0] x[1] \dots x[15]$
00	0011 1111 1111 111	0000 0000 0000 1000
01	0111 1111 1111 111	0000 0000 0000 0100
10	1011 1111 1111 111	0000 0000 0000 1110
11	1111 1111 1111 111	0000 0000 0000 0010

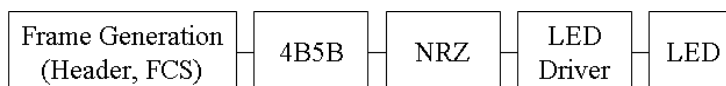
All consecutive packets, including retransmissions, shall be sent with a different initial seed value.

5.5. Line Coding

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.

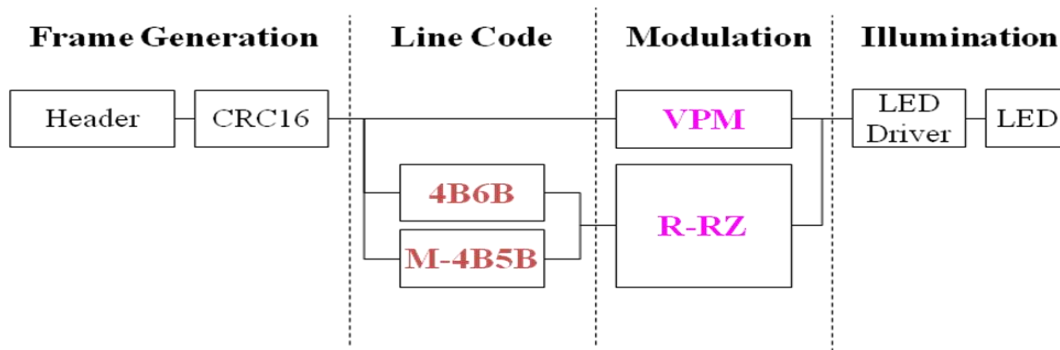
LED illumination MUST satisfy three functions; non-flickering, dimming control, and full brightness.

There is a possible simple model of VLC PHY. PHY frame generation, 4B5B line code, NRZ OOK for modulation, LED driving circuit and LED. This model has a problem when combination of 4B5B and NRZ is used for illumination. First problem is flickering when we transmit data, flickering effect is possible according to data pattern and existence of data frame. Second is a difficulty of dimming control.



(Figure 24) A example of simple VLC PHY

To provide three functions of LED illumination, there are two alternative models. One is VPM (Variable PPM) without line coding, the other is R-RZ (Reverse-RZ) with 4B6B or modified 4B5B.



(Figure 25) PHY models for dimmable and non-flickering illumination

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: $1/\text{minimum flickering free frequency (200Hz)} = 5\text{ms}$

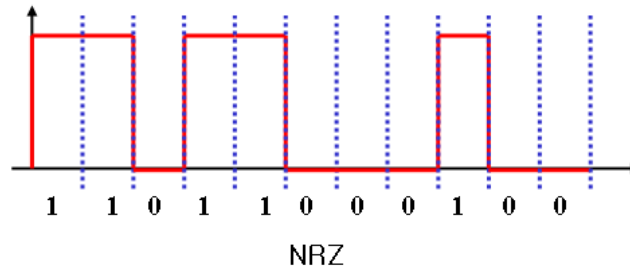
To avoid a flickering from VLC, a brightness of each MFTP must be all equal. There are needed a flickering definition and MFTF (Max Flickering Time Period) by VLC or human eye safety regulation.

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 such as scrambler, modified 4B-5B, and 4B6B.

VLC PHY Line code can use 4B6B, 8B10B, and Modified-4B5B. VLC PHY modulation supports On/off Keying, Variable Pulse Position Modulation (VPM), and Reverse-Return to Zero (R-RZ). PHY supports also Time Division Multiplexing(TDM) for LED signboard.

5.5.1. Modified-4B5B

Line code is the waveform pattern of voltage or current used to represent the 1s and 0s of a digital signal on a transmission link is called line encoding. It is for reliable clock recovery at the receiver or for eliminating DC component which eliminates long sequences consisting of '0' or '1' only.



(Figure 26) An example of flickering from NRZ

NRZ is a very simple and general technology at fiber optical communication. NRZ can make Flickering by data pattern or existence of data frame.

4B5B is a line code that maps 4-bit symbols to 5-bit symbols. 4B5B provides a function of a DC-balance and bounded disparity, and yet provide enough state changes to allow reasonable clock recovery. 4B5B is used at PCI Express, Gigabit Ethernet, and USB 3.0.

(Table 9) Modified-4B5B (M-4B5B)

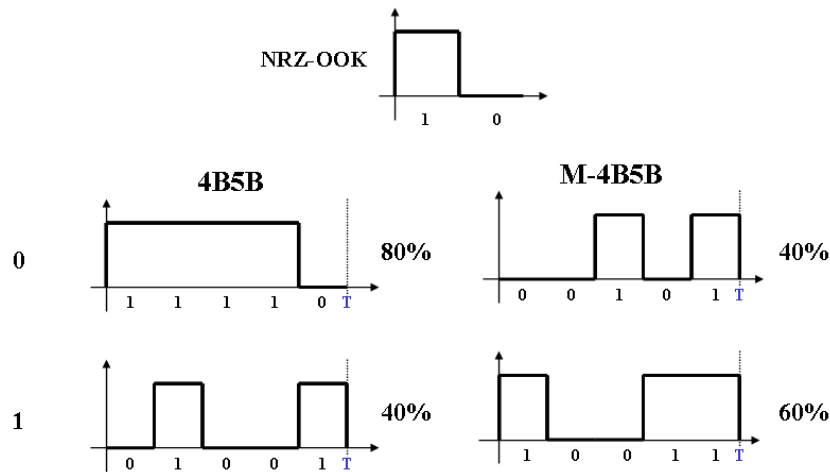
	4B	5B	M-4B5B
0	0000	11110	00101
1	0001	01001	10011
2	0010	10100	00110
3	0011	10101	10101
4	0100	01010	01001
5	0101	01011	10110
6	0110	01110	01010
7	0111	01111	11001
8	1000	10010	01100
9	1001	10011	11010
A	1010	10110	10001
B	1011	10111	01011

C	1100	11010	10010
D	1101	11011	01101
E	1110	11100	10100
F	1111	11101	01110

4B5B cannot support non-flickering because 4B5B is not even pattern at the ratio of 1 and 0. 4B5B has three types of 1 and 0 ratio at its output results, 4:1(80%,5), 3:2(60%,7) and 2:3(40%,4). This percentage means brightness when 1 is on and 0 is off. Brightness difference of 4:1 and 2:3 is too big. Modified-4B5B does not have 4:1 pattern, such as 0, 7, B, C, D, F in case 4B5B. Modified-4B5B produces the output pattern of 4B5B to be 3:2 or 2:3

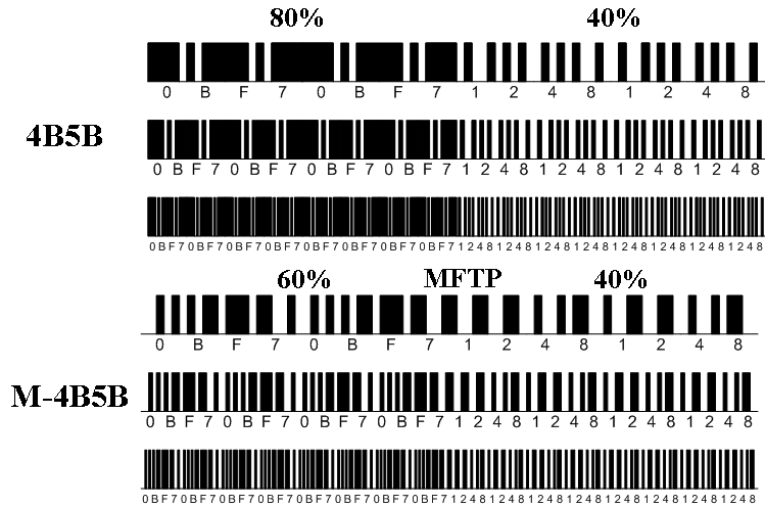
- Idle time pattern : 00011 00111
- Preamble pattern : 11000 11100

Features of M-4B5B are almost 50% duty cycle more than 4B5B, reduced run length 8 to 4 that maintains a coding rate 4/5.



(Figure 27) An example of 4B5B and M-4B5B at NRZ OOK

We can see an example of flickering at NRZ using 4B5B and M-4B5B due to the difference of brightness.



(Figure 28) An example of a flickering at NRZ OOK using 4B5B and M-4B5B

5.5.2. 4B6B

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

- Idle time pattern : 111000 000111
- Preamble pattern : Combination of 110100 and 001011

(Table 1 0) 4B6B

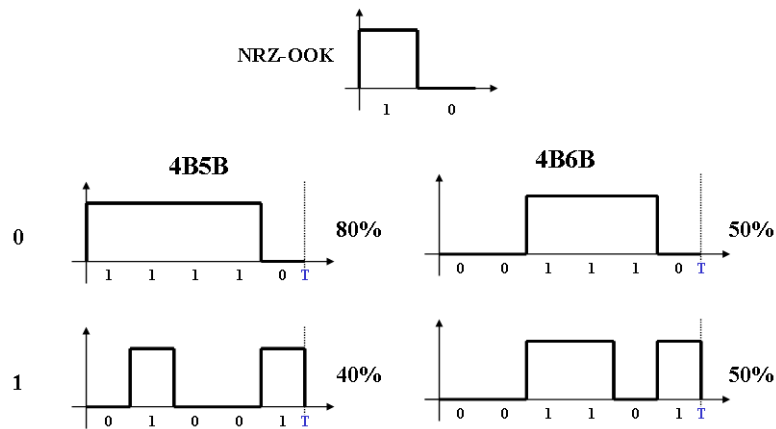
	4B	5B	6B
0	0000	11110	001110
1	0001	01001	001101
2	0010	10100	010011
3	0011	10101	010110
4	0100	01010	010101
5	0101	01011	100011
6	0110	01110	100110
7	0111	01111	100101
8	1000	10010	011001
9	1001	10011	011010
A	1010	10110	011100
B	1011	10111	110001

C	1100	11010	110010
D	1101	11011	101001
E	1110	11100	101010
F	1111	11101	101100

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:

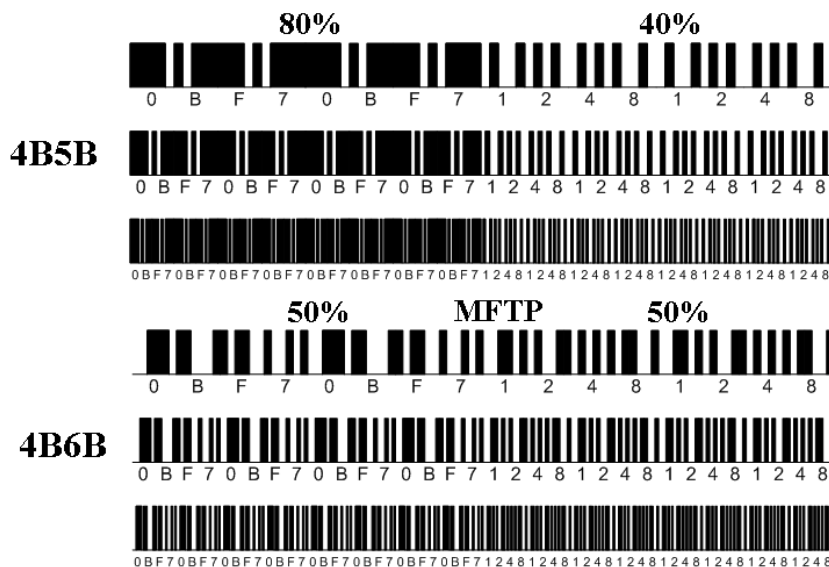
0: 001110 ↔ 001101 : 1

4B6B supports clock recovery and DC-balanced waveform.



(Figure 29) An example of 4B5B and 4B6B at NRZ OOK

There are difference between 4B5B and 4B6B in terms of a flickering. The difference is up to 80% from 40%. 4B6B is always same as 50%.



(Figure 30) A flickering comparison at NRZ OOK using 4B5B and 4B6B

Flickering is a very important factor in terms of illumination. Flickering free technology is required.

5.5.3. 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 1 1) Example of line coding

	(RD-)	D20.7	(RD+)	D7.1	(RD+)
Violation	(RD-)	001011 0111	(RD+)	111000 1001	(RD+)
Correct	(RD-)	001011 0111	(RD+)	000111 1001	(RD+)

5.6. Modulation

Several modulation methods are used in high data rate PHY. CCM (Color Code Modulation), HHW (High Hamming Weight) code, 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.

5.6.1. 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.

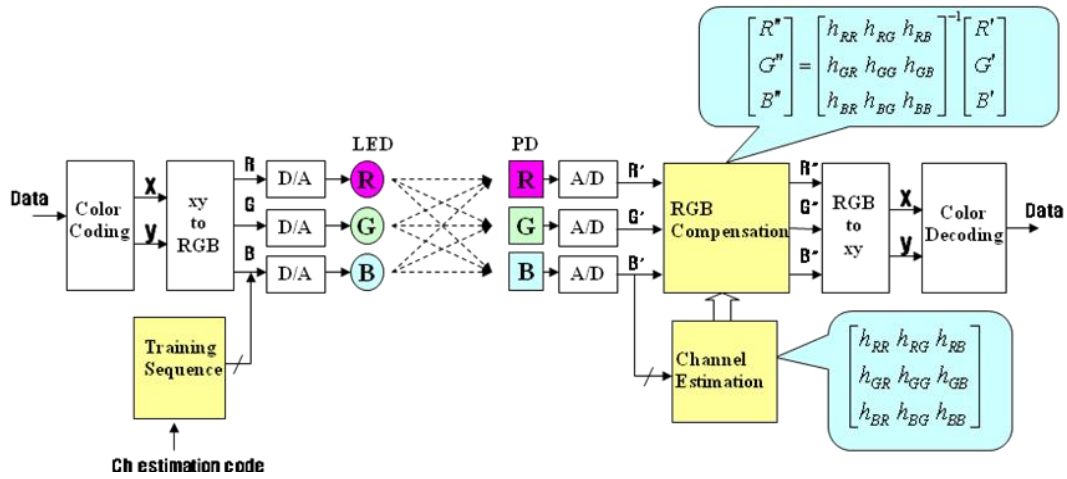
5.6.2. CCM (Color Code Modulation)

(Table 1 2) Next figure is proposed Data rate for CCM mode

(Table 1 2) Data rate for CCM mode

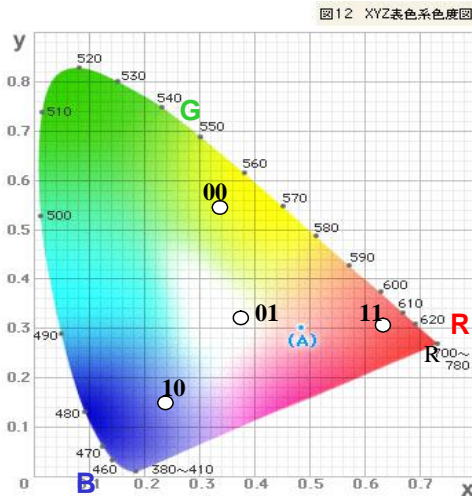
Channel coding	CCM type	Sampling Frequency 4x	Uncoded data rate
2/3	4 CCM	24	8
1 (No channel coding)	4 CCM	24	12
2/3	8 CCM	48	24
1	8 CCM	48	36
2/3	8 CCM	96	48
1	8 CCM	96	72
2/3	16 CCM	96	64
1	16 CCM	96	96

CCM (Color Code Modulation) is a new modulation scheme proposed for the standard. It does not depend on the wave length and number directly. It can be expected better flexibility for VLC system than WDM.



(Figure 31) CCM modulation (scrambler and FEC not shown)

First, transmit data is coded by the color coding block into xy values according to the xy color coordinate.



(Figure 32) CIE1931 xy color coordinate

Fig. 32 shows the CIE1931 xy color coordinate with the example for CCM symbol positions. All visible colors in the color palette defined by xy values. And the numbers around the color palette show the wave lengths at each single tone color. R,G,B figures shows the center wave length of the actual RGB LED devices. In this case, 4 Symbol points are placed in the RGB triangle. That means this system can send 2 bits data information per symbol. Next, these xy values are transformed into RGB values. The relation between xy and RGB is showed by following equations (according to “CIE1931 RGB color space”).

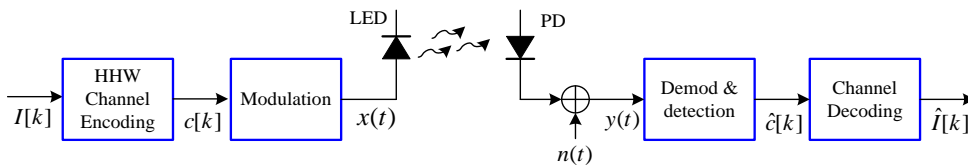
$$\begin{aligned}
 X &= 2.7689R + 1.7517G + 1.1302B \\
 Y &= R + 4.5907G + 0.0601B \\
 Z &= 0.0565G + 5.5943B \\
 x &= X / (X + Y + Z) \\
 y &= Y / (X + Y + Z)
 \end{aligned}$$

Those coefficients are defined by the RGB wave length. In this case RGB wave length are these (R:700nm, G:546.1nm, B:435.8nm). 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 values like WDM.

5.6.3. HHW (High Hamming Weight) code

To improve the illumination ability as well as retain the quality of communication, HHW is proposed. Under the same peak power constraint, we intensively force the output of channel encoder to select the codeword with high Hamming weight out of two candidate codewords by which the average amplitude level can be increased.

The system block diagram is illustrated in Fig. below. At the transmitter side, the transmit data is encoded by HHW channel encoder. The output is modulated by a certain level line code such as NRZ, OOK, and etc.



(Figure 33) HHW block diagram (scrambler and FEC not shown)

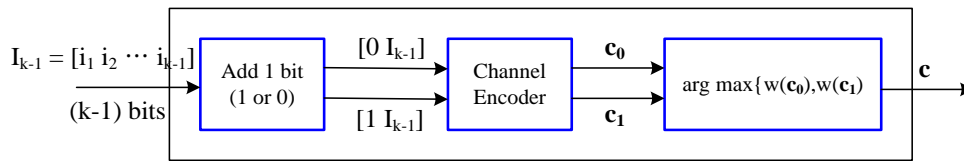
5.6.3.1. HHW channel encoder

HHW attempts to make codeword have high Hamming weight on average by choosing one of the two codewords with different Hamming weight. It needs to waste an information bit for this comparison, which is operated even when we use multiple information bits to improve the density of 1's. In Figure ??, the block diagram of HHW channel encoder is illustrated. The proposed algorithm is as follows:

- a) Generate (k-1) information bits for any (n,k) channel code.
- b) Adding an additional bit, make two k-bits messages.
- c) Generate two codewords using channel encoder.
- d) Calculate Hamming weights for two codewords and choose higher one.

$$\mathbf{c} = \arg \max_{\{\mathbf{c}_0, \mathbf{c}_1\}} \{w(\mathbf{c}_0), w(\mathbf{c}_1)\}, \text{ where } w(\mathbf{c}_i) \text{ is sum of 1's weight}$$

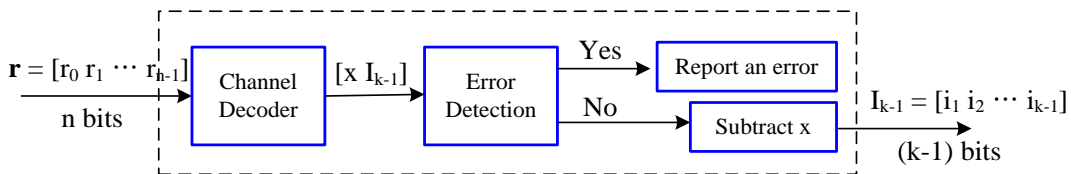
- e) Forward the codeword to modulator.



(Figure 34) HHW channel encoder

5.6.3.2. HHW channel decoder

The below figure is HHW channel decoding block. Decoding of received codeword is based on traditional channel decoder since all the codewords of HHW are included in a codeword set of traditional one. The k-bits of information including a dummy bit which is used for illumination is decoded, and the (k-1) bits of information can be taken after subtracting the dummy bit. HHW has error detection capability partially since the error is detected when the k-bit information for unused codeword is decoded.



(Figure 35) HHW channel decoder

5.6.4. Variable PPM

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

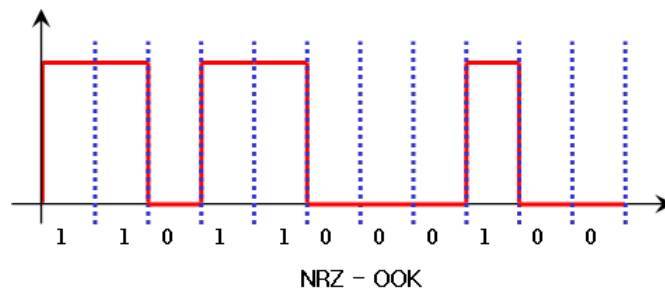
A flicker LED light due to VLC modulation is not good for eye safety. We need a modulation to remove the flicker for eye safety. If we cannot remove the flicker in VLC for illumination, no one use a VLC as an illumination.

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.

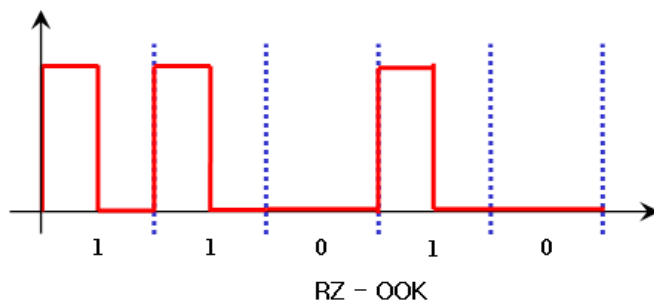
There are several candidates of VLC modulation as well as LED illumination. We can consider the modulation such as NRZ – OOK, RZ – OOK, PPM, I-PPM, PWM, and VPM.

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.



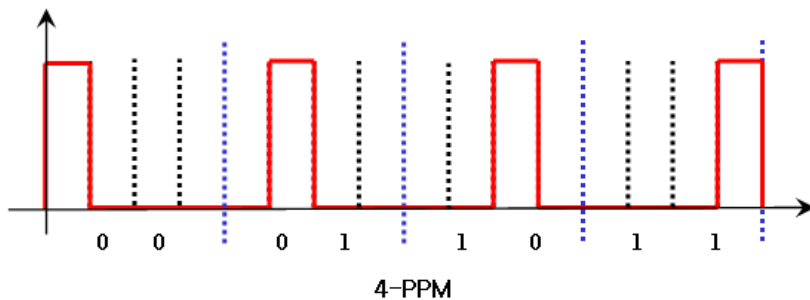
(Figure 36) An example of NRZ - OOK

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.



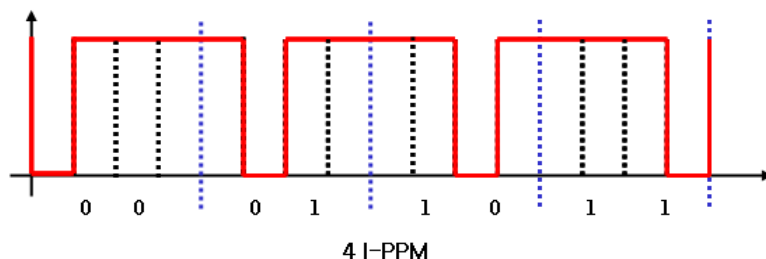
(Figure 37) An example of RZ - OOK

PPM (Pulse Position Modulation) is that M message bits are encoded by transmitting a single pulse in one of 2^M 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 38) An example of PPM (Pulse Position Modulation)

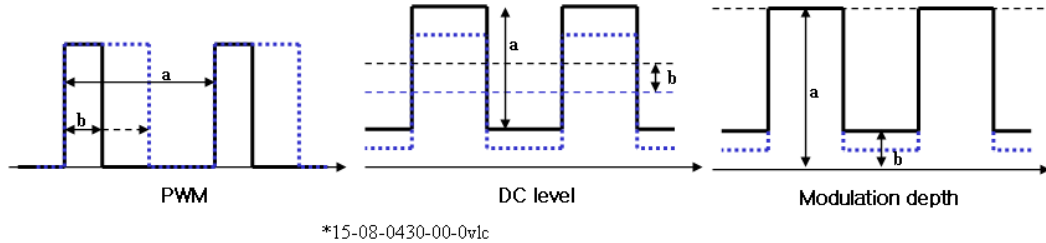
I - PPM (Inverse - PPM) is that M message bits are encoded by transmitting a single pulse in one of 2^M possible time-shifts. I-PPM is a good modulation for the non-flickering and the full brightness. But it is difficult to achieve the dimming control.



(Figure 39) An example of I-PPM (Inverse Pulse Position Modulation)

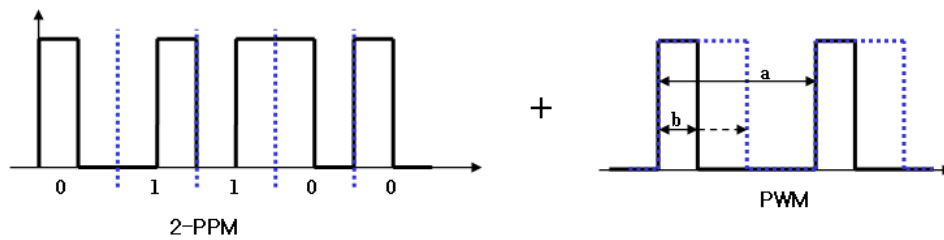
PWM (Pulse Width Modulation) is the modulation scheme widely used in LED illumination for itself. So, we can basically achieve the flicker-free, the dimming control, and the full brightness by using PWM. If

we use PWM only itself for VLC, we cannot obtain the flickering-free, the dimming control, or the full brightness.



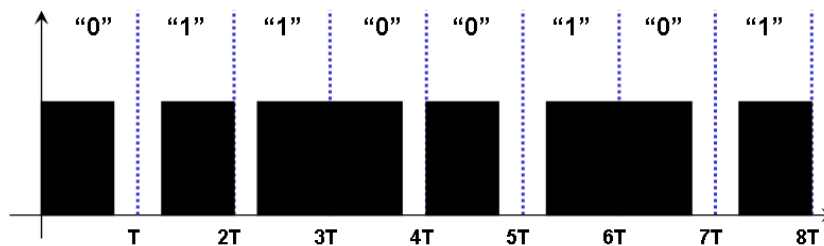
(Figure 40) An example of PWM (Pulse Width Modulation)

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 %.



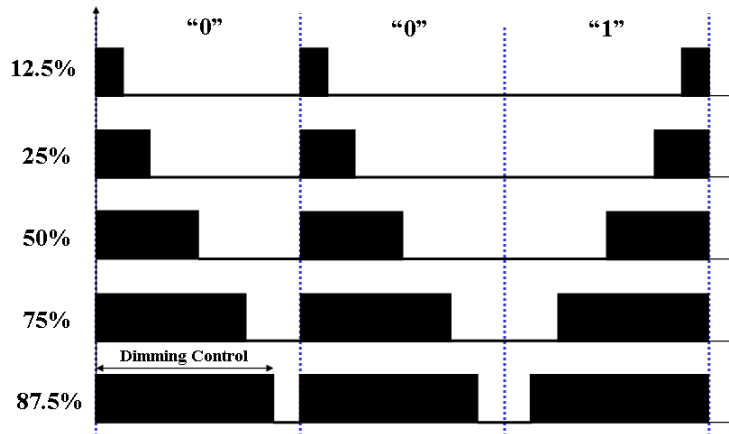
(Figure 41) The basic concept of Variable PPM

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 42) 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.

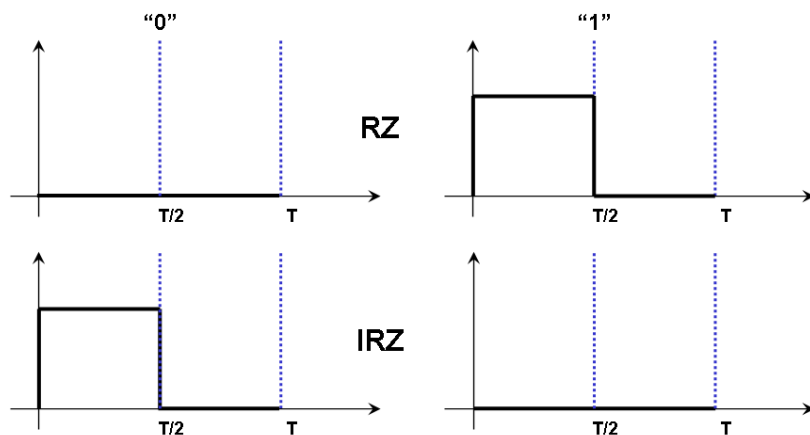


(Figure 43) An example of Dimming Control by VPM Signal

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.

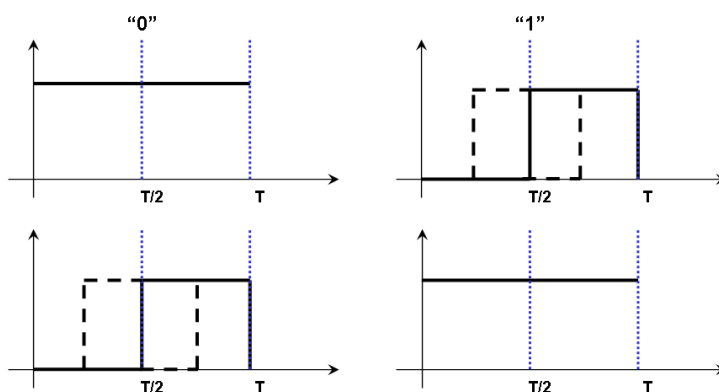
5.6.5. Reverse-RZ with Variable Duty: RRZ

Reverse-RZ with variable duty provides a dimming control, but not supports function of non-flickering. Reverse-RZ is an advanced modulation scheme from RZ (Return to Zero) and IRZ (Inverse Return to Zero). The waveform of conventional RZ defines 0 zero to zero and 1 zero to one to zero. The waveform of Inverse RZ is the inversed one from RZ.



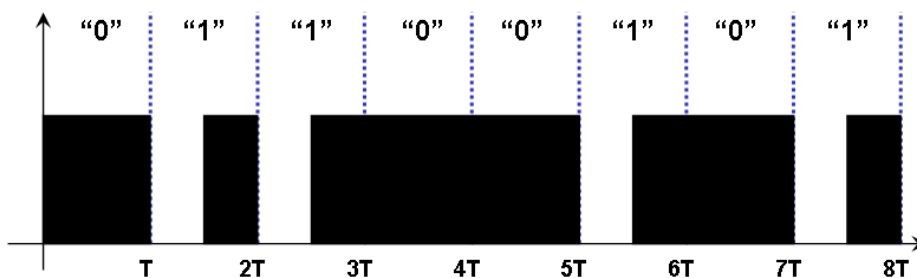
(Figure 44) A basic signal of Typical RZ and IRZ

Reverse-RZ defines that digit “0” signal is no transition signal or this one and digit “1” signal can be controlled by the duty cycle. The controlling of the duty cycle provides the dimming scheme for LED illumination.



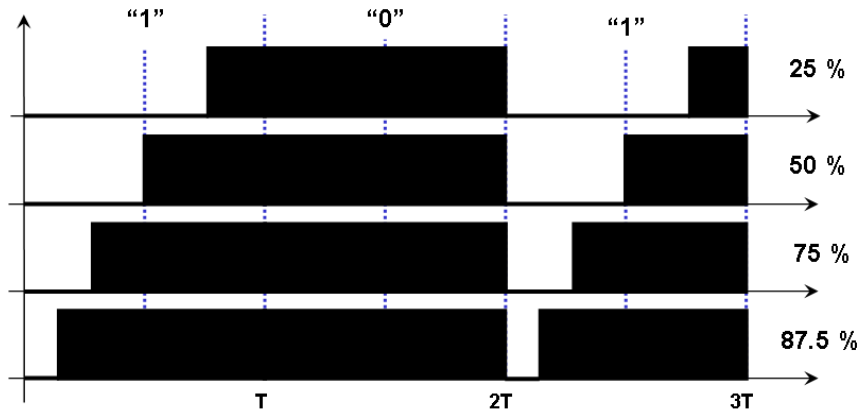
(Figure 45) A basic signal of Reverse RZ with 50% dimming

We can control the waveform of R-RZ with 50 % duty cycle when we need dimming the illumination lighting with 50%. In R-RZ, the flicker may happen because the “on” state area may not be constant during each time period. When we need a flicker free signal in R-RZ, 4B6B provides it.



(Figure 46) Example Waveform of Proposed Reverse-RZ Signal with 50% duty

R-RZ waveforms provide the dimming function according to controlling of duty cycle. The dimming control can be achieved by adjusting of a duty and the full brightness by increase of duty cycle resolution. Dimming control in this modulation scheme is similar to the VPM.



(Figure 47) Dimming Control of Reverse-RZ Signal with Variable Duty

Advantages of Reverse-RZ with variable duty can provide dimming control by the duty cycle adjustment and full brightness by the increase of the duty cycle resolution. It also provide flicker-free signal by using R-RZ with 4B6B or advanced 4B-5B line codes. 4B6B or advanced 4B-5B line codes makes the “on” state area of LED light be always constant under the given duty cycle.

We can choose a specific modulation depending on VLC application. There are several applications with different requirement. A VLC application such as cellular phone to cellular phone needs only high speed regardless flickering, dimming, and full brightness. The other application such as LED illumination needs non-flickering, dimming, and full brightness regardless communication speed. The table shows the comparison of modulations: NRZ-OOK, RZ-OOK, PPM, I-PPM, PWM, VPM, R-RZ.

(Table 1 3) Comparison and Our Proposal of VLC Modulation Scheme for Illumination

	Flickering-free	Dimming Control	Full Brightness
NRZ-OOK	O / w LC	X	X
RZ-OOK	O / w LC	X	X
PPM	O	X	X
I-PPM	O	X	O
PWM (not for VLC)	O	O	O
VPM	O	O	O
R-RZ	O / w LC	O	O

(w LC : with Line Code)

VPM provide the function of a flicker-free, dimmable and full brightness VLC signal for illumination. R-RZ also provide dimmable and full brightness VLC signal for illumination.

5.7. Channel Coding

We propose the use of FEC for VLC.

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 $GF(2^8)$ with a primitive polynomial $p(z) = z^8 + z^4 + z^3 + z^2 + 1$, where α is the root of the polynomial $p(z)$. For brevity, this Galois field is denoted as F . As notation, the element $M = b_7z^7 + b_6z^6 + b_5z^5 + b_4z^4 + b_3z^3 + b_2z^2 + b_1z + b_0$, where $M \in F$, has the following binary representation $b_7b_6b_5b_4b_3b_2b_1b_0$, where b_7 is the MSB and b_0 is the LSB

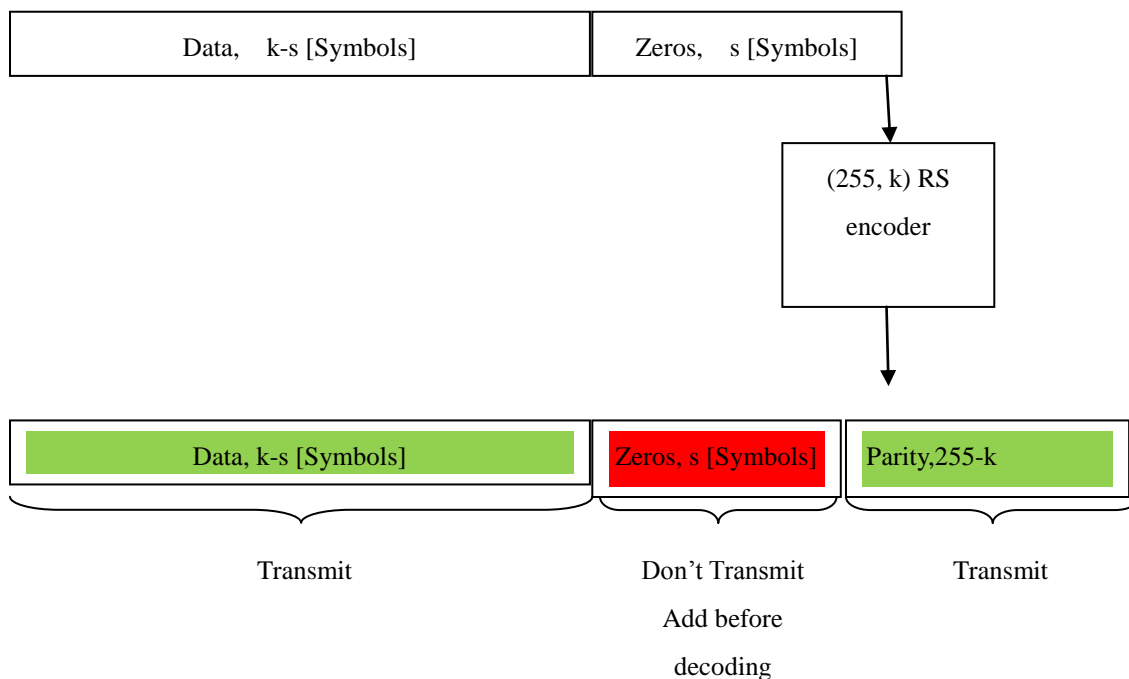
The generator polynomial is obtained by shortening a systematic (255, k) Reed-Solomon code, which is specified by the generator polynomial

$g(x) = (x - \alpha^i) = x^6 + 126x^5 + 4x^4 + 158x^3 + 58x^2 + 49x + 117$, where $g(x)$ is the generator polynomial over F , $x \in F$ 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 48) Shortened RS code generation

5.8. Color Quality Indicator support:

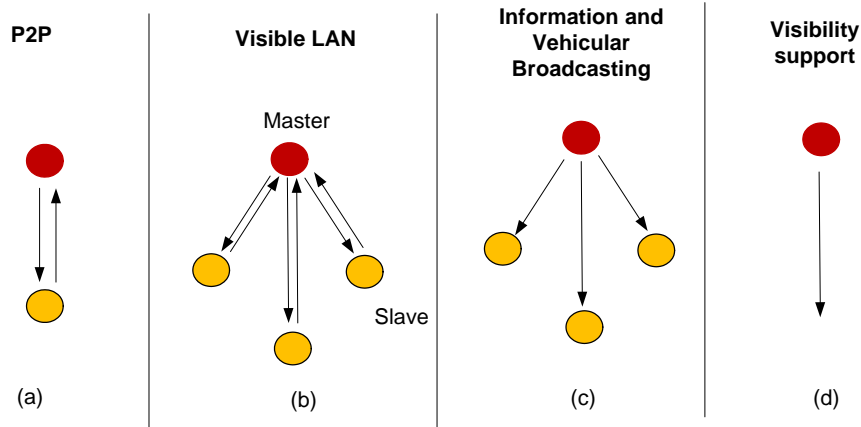
A device shall be capable of estimating the link quality of the received color channel, where the color quality shall be defined as an estimate of the SNR available after the CDR and will include all implementation losses associated with that particular receiver architecture (quantization noise, channel 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. MAC sub layer specification

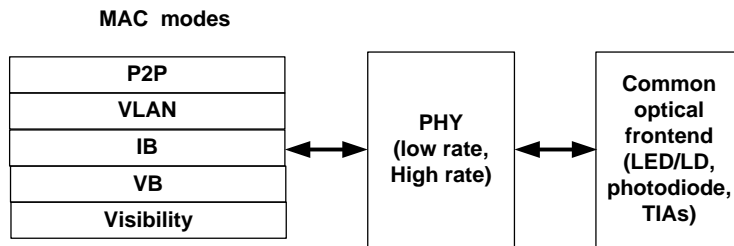
This clause specifies the MAC sub layer of this standard. The MAC sub layer handles all access to the physical radio channel and is responsible for the following tasks:

- 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
- Full brightness scheme
- Supporting signboard for broadcasting
- Supporting color packets for link establishment and packet error identification
- Supporting device security
- Providing a reliable link between two peer MAC entities

The standard provides a single MAC that supports P2P, VLAN, IB, VB and visibility modes for VLC communication. 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. With such an integrated solution, front-end optics such as the optical light source such as LEDs or laser diodes (LDs) and drivers, the receiving photodiodes, transimpedance amplifiers (TIA) and parts of the PHY and MAC protocols can be shared for multiple modes while simultaneously making it possible to make a single low complexity device that supports all these modes.



(Figure 49) MAC topologies supported



(Figure 50) MAC modes of operation (single MAC)

6.1. MAC frame formats

This sub clause 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 sub layer are described as a sequence of fields in a specific order. All frame formats in this sub clause 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.

6.1.1. 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.

(Table 1 4) General MAC frame format

Octets: 2	1	0/2/8	0/2	0/2/8	0/5/6/10/14	variable	2	
Frame Control	Sequence Number	Destination Address	Source PAN Identifier	Source Address	Auxiliary Security Header	Frame Payload	FCS	
		Addressing fields						
MHR							MAC Payload	MFR

6.1.1.1. 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 below

(Table 1 5) Format of the Frame Control field

Bits: 0-2	3	4	5-6	7	8-9	10-11	12-13	14-15
Frame Type	Security Enabled	Frame Pending	Ack. Request Policy	PAN ID Compression	Reserved	Dest. Addressing Mode	Frame Version	Source Addressing Mode

6.1.1.1.1. Frame Type subfield

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

(Table 1 6) 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	<i>Reserved</i>

6.1.1.1.2. 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 sub layer 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.

6.1.1.1.3. 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.

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 PAN or at any time by devices operating on a nonbeacon-enabled PAN.

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

6.1.1.1.4. Acknowledgment Request subfield

The Acknowledgment Request subfield is 2 bits in length and specifies whether an acknowledgment is required from the recipient device on receipt of a data or MAC command frame and the acknowledgement type. If this subfield is set to non-zero value, the recipient device shall send an acknowledgment frame only if, upon reception, the frame passes the third level of filtering. If this subfield is set to zero, the recipient device shall not send an acknowledgment frame.

(Table 1 7) Acknowledgment Request subfield

Value	ACK Policy	Description
0	No ACK	
1	Immediate ACK	Responds immediately
2	Block ACK	Keeps track of frames received and responds after receiving request to respond
3	Block ACK request	

6.1.1.1.5. PAN ID Compression subfield

The PAN ID Compression subfield is 1 bit in length and specifies whether the MAC frame is to be sent containing only one of the PAN 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 PAN Identifier field, and the Source PAN 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 PAN Identifier and Destination PAN Identifier fields. If only one of the addresses is present, this subfield shall be set to zero, and the frame shall contain the PAN 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 PAN identifier field.

6.1.1.1.6. 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.

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 PAN coordinator with the PAN identifier as specified in the Source PAN Identifier field.

(Table 1 8) Possible values of the Destination Addressing Mode and Source Addressing Mode subfields

Addressing mode value $b_1 b_0$	Description
00	PAN identifier and address fields are not present.
01	Reserved.
10	Address field contains a 16-bit short address.
11	Address field contains a 64-bit extended address.

6.1.1.1.7. 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 current standard version. It is reserved for future extensions.

6.1.1.1.8. 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.

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 PAN coordinator with the PAN identifier as specified in the Destination PAN Identifier field.

6.1.1.1.9. 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.

6.1.1.1.10. 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 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.

6.1.1.1.11. Source PAN Identifier field

The Source PAN Identifier field, when present, is 2 octets in length and specifies the unique PAN identifier of the originator of the frame. This field shall be included in the MAC frame only if the Source Addressing Mode and PAN ID Compression subfields of the Frame Control field are nonzero and equal to zero, respectively.

The PAN identifier of a device is initially determined during association on a PAN, but may change following a PAN identifier conflict resolution.

6.1.1.1.12. 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 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 nonzero.

6.1.1.1.13. 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. This field shall be present only if the Security Enabled subfield is set to one.

6.1.1.1.14. 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.

6.1.1.1.15. 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:

$$G_{16}(x) = x^{16} + x^{12} + x^5 + 1$$

The FCS shall be calculated for transmission using the following algorithm:

Let $M(x) = b_0x^{k-1} + b_1x^{k-2} + \dots + b_{k-2}x + b_{k-1}$ be the polynomial representing the sequence of bits

for which the checksum is to be computed.

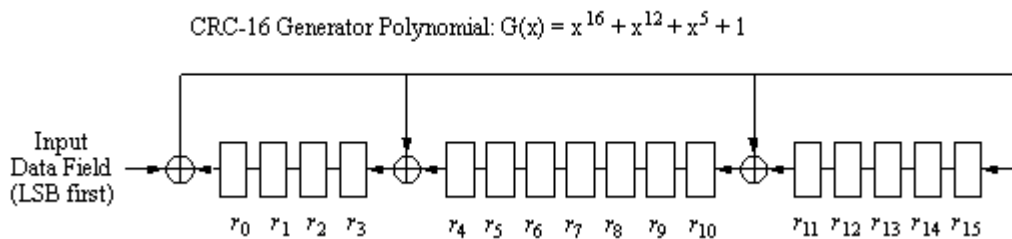
Multiply $M(x)$ by x^{16} , giving the polynomial $x^{16} \times M(x)$.

Divide $x^{16} \times M(x)$ modulo 2 by the generator polynomial, $G_{16}(x)$, to obtain the remainder polynomial,

$$R(x) = r_0x^{15} + r_1x^{14} + \dots + r_{14}x + r_{15}$$

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.



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 51) Typical FCS implementation

6.1.2. Format of individual frame types

Five frame types are defined: beacon, data, acknowledgment, MAC command and visibility. These frame types are discussed below

6.1.2.1. Beacon frame format

The beacon frame shall be formatted as illustrated in Figure 82.

(Table 1 9) Beacon frame format

Octets: 2	1	4/10	0/5/6/10/14	3	variable	variable	variable	2
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	Superframe Specification	GTS fields	Pending address fields	Beacon Payload	FCS
MHR				MAC Payload				MFR

The GTS fields shall be formatted as illustrated and the pending address fields shall be formatted as illustrated.

Octets: 1	0/1	variable
GTS Specification	GTS Directions	GTS List

(Table 2 0) Format of the GTS information fields

Octets: 1	variable
Pending Address Specification	Address List

(Table 2 1) 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.

6.1.2.1.1. Beacon frame MHR fields

The MHR for a beacon frame shall contain the Frame Control field, the Sequence Number field, the Source PAN 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, 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 PAN Identifier and Source Address fields shall contain the PAN 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.

6.1.2.1.2. Superframe Specification field

The Superframe Specification field is 24 bits in length and shall be formatted as illustrated

(Table 2 2) Format of the Superframe Specification field

Bits: 0– 3	4-7	8-11	12	13-16	17-19	20	21	22-23
Beacon Order	Superfra me Order	Final CAP Slot	Battery Life Extension (BLE)	Final uplink slot	Reserved	PAN Coordinator	Association Permit	Operating mode

The Beacon Order subfield is 4 bits in length and shall specify the transmission interval of the beacon. 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.

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

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 Final uplink Slot subfield is 4 bits in length and specifies the final superframe slot utilized by the uplink. The duration of the uplink, as implied by this subfield, shall be greater than or equal to the value specified by *aMinUplinkSlotLength*.

The PAN Coordinator subfield is 1 bit in length and shall be set to one if the beacon frame is being transmitted by the PAN coordinator. Otherwise, the PAN 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 PAN). The association permit bit shall be set to zero if the coordinator is currently not accepting association requests on its network.

The operating mode field for the beacon is 2 bits in length.

(Table 2 3) The operating mode field for the beacon

Bits	Mode
00	IB
01	VB
10	VLAN
11	<i>Reserved</i>

6.1.2.1.3. GTS Specification field

The GTS Specification field is 8 bits in length and shall be formatted as illustrated.

Bits: 0-2	3-6	7
GTS Descriptor Count	Reserved	GTS Permit

(Table 2 4) 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 PAN coordinator is accepting GTS requests). Otherwise, the GTS Permit field shall be set to zero.

6.1.2.1.4. GTS Directions field

The GTS Directions field is 8 bits in length and shall be formatted as illustrated.

Bits: 0-6	7
GTS Directions Mask	Reserved

(Table 2 5) 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.

6.1.2.1.5. 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.

Bits: 0-15	16-19	20-23
Device Short Address	GTS Starting Slot	GTS Length

(Table 2 6) 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.

6.1.2.1.6. Pending Address Specification field

The Pending Address Specification field shall be formatted as illustrated

Bits: 0-2	3	4-6	7
Number of Short Addresses Pending	Reserved	Number of Extended Addresses Pending	Reserved

(Table 2 7) 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.

6.1.2.1.7. 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.

6.1.2.1.8. Beacon Payload field

The Beacon Payload field is an optional sequence of up to *aMaxBeaconPayloadLength* octets specified to be transmitted in the beacon frame, 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 2 8) 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 2 9) 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	

6.1.2.2. 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 3 0) 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 3 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

6.1.2.3. 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 3 2) 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.

6.1.2.4. Data frame format

The data frame shall be formatted as illustrated in Data frame format.

Octets: 2	1		0/5/6/10/14	1	variable	2
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	Data type	Data Payload	FCS
	MHR			MAC Payload		MFR
	(Table 3 3) Data frame format					

The order of the fields of the data frame shall conform to the order of the general MAC frame as illustrated.

6.1.2.4.1. Data frame MHR fields

The MHR for a data frame shall contain the Frame Control field, the Sequence Number field, the destination PAN identifier/address fields, and/or the source PAN identifier/address fields.

In the Frame Control field, the Frame Type subfield shall contain the value that indicates a data frame, as shown in Values of the Frame Type subfield. 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.

6.1.2.4.2. Data Payload field

(Table 3 4) The data type field is 1 byte and is explained in table below.

Bits 0-1	Bits 2-7
00 – Single	Num PDUs per data frame
01 – Packed	
10 – Burst	
11 - Reserved	

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.

6.1.2.5. Acknowledgment frame format

The acknowledgment frame for immediate ACK shall be formatted as illustrated in Acknowledgment frame format.

Octets: 2	1	2
Frame Control	Sequence Number	FCS
MHR		MFR

(Table 3 5) Acknowledgment frame format

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 52) 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 53) 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.

6.1.2.5.1. 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 Values of the Frame Type subfield. 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, 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.

6.1.2.6. MAC command frame format

The MAC command frame shall be formatted as illustrated in MAC command frame format.

Octets: 2	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

(Table 3 6) 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.

6.1.2.6.1. MAC command frame MHR fields

The MHR for a MAC command frame shall contain the Frame Control field, the Sequence Number field, the destination PAN identifier/address fields and/or the source PAN 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 Values of the Frame Type subfield. 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.. 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.

6.1.2.6.2. Command Frame Identifier field

The Command Frame Identifier field identifies the MAC command being used. This field shall be set to one of the non-reserved values.

6.1.2.6.3. Command Payload field

The Command Payload field contains the MAC command itself.

6.1.3. Frame compatibility

6.2. MAC command frames

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 PANs or at any time for nonbeacon-enabled PANs.

Command frame identifier	Command name
0x01	Association request
0x02	Association response
0x03	Disassociation notification
0x04	Data request
0x05	PAN ID conflict notification
0x06	Orphan notification
0x07	Beacon request
0x08	Coordinator realignment
0x09	GTS request
0x0a	Blinking notification
0x0b	Dimming notification
0x0c	Fast link recovery signaling
0x0d	Mobility notification
0x0e	Information element exchange
0x0f–0xff	Reserved

6.2.1. Association request command

The association request command allows a device to request association with a PAN through the PAN coordinator or a coordinator.

This command shall only be sent by an unassociated device that wishes to associate with a PAN. A device shall only associate with a PAN through the PAN 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 Association request command format.

octets:	1	1
MHR fields	Command Frame Identifier	Capability Information

(Table 3 7) Association request command format

6.2.1.1. 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 PAN Identifier field shall contain the identifier of the PAN 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 PAN Identifier field shall contain the broadcast PAN identifier (i.e., 0xffff). The Source Address field shall contain the value of *aExtendedAddress*.

6.2.1.2. Capability Information field

The Capability Information field shall be formatted as illustrated

bits: 0	1	2	3	4-5	6	7
Alternate PAN Coordinator	Device Type	Power Source	Receiver On When Idle	Battery information	Security Capability	Allocate Address

(Table 3 8) Capability Information field format

The Alternate PAN Coordinator subfield is 1 bit in length and shall be set to one if the device is capable of becoming the PAN coordinator. Otherwise, the Alternate PAN 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.

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; 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.

6.2.1.3. Association response command

The association response command allows the PAN 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 PAN 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

octets:	1	2	1
MHR fields	Command Frame Identifier	Short Address	Association Status

(Table 3 9) Association response command format

6.2.1.4. 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 PAN ID Compression subfield of the Frame Control field shall be set to one. In accordance with this value of the PAN ID Compression subfield, the Destination PAN Identifier field shall contain the value of *macPANId*, while the Source PAN 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*.

6.2.1.5. Short Address field

If the coordinator was not able to associate this device to its PAN, 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 PAN, this field shall contain the short address that the device may use in its communications on the PAN until it is disassociated.

A Short Address field value equal to 0xfffe shall indicate that the device has been successfully associated with a PAN, but has not been allocated a short address. In this case, the device shall communicate on the PAN using only its 64-bit extended address.

6.2.1.6. Association Status field

The Association Status field shall contain one of the nonreserved values listed

(Table 4 0) Valid values of the Association Status field

Association status	Description
0x00	Association successful.
0x01	PAN at capacity.
0x02	PAN access denied.
0x03–0x7f	Reserved.
0x80–0xff	Reserved for MAC primitive enumeration values.

6.2.1.7. Disassociation notification command

The PAN 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.

octets:	1	1
MHR fields	Command Frame Identifier	Disassociation Reason

(Table 4 1) Disassociation notification command format

6.2.1.8. 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 PAN ID Compression subfield of the Frame Control field shall be set to one. In accordance with this value of the PAN ID Compression subfield, the Destination PAN Identifier field shall contain the value of *macPANId*, while the Source PAN Identifier field shall be omitted. If the coordinator wants an associated device to leave the PAN, then the Destination Address field shall contain the address of the device being removed from the PAN. If an associated device wants to leave the PAN, 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*.

6.2.1.9. Disassociation Reason field

The Disassociation Reason field shall contain one of the nonreserved values.

(Table 4 2) Valid disassociation reason codes

Disassociate reason	Description
0x00	Reserved.
0x01	The coordinator wishes the device to leave the PAN.
0x02	The device wishes to leave the PAN.
0x03–0x7f	Reserved.
0x80–0xff	Reserved for MAC primitive enumeration values.

6.2.2. Data request command

The data request command is sent by a device to request data from the PAN coordinator or a coordinator.

There are three cases for which this command is sent. On a beacon-enabled PAN, 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.

octets:	1
MHR fields	Command Frame Identifier

(Table 4 3) 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 that it originated from the PAN coordinator 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 0xffff, 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 0xffff, 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 0xffff, 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 PAN ID Compression subfield of the Frame Control field shall be set to zero and the source PAN identifier shall contain the value of *macPANId*. Otherwise, the PAN ID Compression subfield shall be set to one. In this case and in accordance with the PAN ID Compression subfield, the Destination PAN Identifier field shall contain the value of *macPANId*, while the Source PAN 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.

6.2.3. PAN ID conflict notification command

The PAN ID conflict notification command is sent by a device to the PAN coordinator when a PAN 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 PAN ID conflict notification command shall be formatted as illustrated..

octets:	1
MHR fields	Command Frame Identifier

(Table 4 4) PAN 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 PAN ID Compression subfield of the Frame Control field shall be set to one. In accordance with this value of the PAN ID Compression subfield, the Destination PAN Identifier field shall contain the value of *macPANId*, while the Source PAN 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*.

6.2.4. 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.

octets: 15	1
MHR fields	Command Frame Identifier

(Table 4 5) 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 PAN ID Compression subfield of the Frame Control field shall be set to one. In accordance with this value of the PAN ID Compression subfield, the Destination PAN Identifier field shall contain the value of the broadcast PAN identifier (i.e., 0xffff), while the Source PAN 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*.

6.2.5. 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.

octets: 7	1
MHR fields	Command Frame Identifier

(Table 4 6) 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 PAN Identifier field shall contain the broadcast PAN identifier (i.e., 0xffff). The Destination Address field shall contain the broadcast short address (i.e., 0xffff).

6.2.6. Coordinator realignment command

The coordinator realignment command is sent by the PAN coordinator or a coordinator either following the reception of an orphan notification command from a device that is recognized to be on its PAN or when any of its PAN 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 PAN configuration attributes (i.e., PAN identifier, short address, logical channel, or channel page) change, it is broadcast to the PAN.

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.

octets: 17/18/23/24	1	2	2	1	2	0/1
MHR fields	Command Frame Identifier	PAN Identifier	Coordinator Short Address	Logical Channel	Short Address	Channel page

(Table 4 7) Coordinator realignment command format

6.2.6.1. 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 PAN. 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 PAN.

The Frame Version subfield shall be set to 0x01 if the Channel Page field is present.

The Destination PAN Identifier field shall contain the broadcast PAN 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 PAN Identifier field shall contain the value of *macPANId*, and the Source Address field shall contain the value of *aExtendedAddress*.

6.2.6.2. PAN Identifier field

The PAN Identifier field shall contain the PAN identifier that the coordinator intends to use for all future communications.

6.2.6.3. Coordinator Short Address field

The Coordinator Short Address field shall contain the value of *macShortAddress*.

6.2.6.4. Logical Channel field

The Logical Channel field shall contain the logical channel that the coordinator intends to use for all future communications.

6.2.6.5. Short Address field

If the coordinator realignment command is broadcast to the PAN, 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 PAN. 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 0xffffe.

6.2.6.6. 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.

6.2.7. 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 PAN coordinator. Only devices that have a 16-bit short address less than 0xffffe shall send this command.

This command is optional.

The GTS request command shall be formatted as illustrated.

octets: 7	1	1
MHR fields	Command Frame Identifier	GTS Characteristics

(Table 4 8) GTS request command format

6.2.7.1. 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 PAN Identifier field shall contain the value of *macPANId*, and the Source Address field shall contain the value of *macShortAddress*.

6.2.7.2. GTS Characteristics field

The GTS Characteristics field shall be formatted as illustrated.

bits: 0–3	4	5	6–7
GTS Length	GTS Direction	Characteristics Type	Reserved

(Table 4 9) 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.

6.2.8. Blinking notification command

octets: 7	1	1	2
MHR fields	Command Frame Identifier	Blinking frequency	Blinking color (band plan)

(Table 5 0) Blinking notification command format

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

6.2.9. Dimming notification command

octets: 7	1	2	2
MHR fields	Command Frame Identifier	Dimming level	Dimming link adaptation timer

(Table 5 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.

6.2.10. Mobility notification command

octets: 7	1	xx
MHR fields	Command Frame Identifier	Mobility fields

(Table 5 2) 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

6.2.11. Information element exchange command

See beacon payload section of this document.

6.3. Visibility frame

Octets: 2	2	variable
Frame	Visibility	Visibility
Control	level	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 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.

6.4. MAC functional description

This sub clause provides a detailed description of the MAC functionality. Contention-free access is controlled entirely by the PAN coordinator through the use of GTSSs.

The mechanisms used for starting and maintaining a PAN are described. 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 PAN, the results of a channel scan can be used to select an appropriate logical channel and channel page, as well as a PAN identifier that is not being used by any other PAN in the area. Because it is still possible for the POS of two PANs with the same PAN identifier to overlap, a procedure exists to detect and resolve this situation. Following a channel scan and suitable PAN identifier selection, an FFD can begin operating as the PAN coordinator. Also described in the sub clause is a method to allow a beaconing FFD to discover other such devices during normal operations, i.e., when not scanning.

The association procedure describes the conditions under which a device may join a PAN 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.

. Synchronization on a beacon-enabled PAN is described after first explaining how a coordinator generates beacon frames. Following this explanation, synchronization on a nonbeacon-enabled PAN 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 PAN.

This standard has been designed so that application data transfers can be controlled by the devices on a PAN rather than by the coordinator.

The mechanisms for transmitting, receiving, and acknowledging frames, including frames sent using indirect transmission, are described. In addition, methods for retransmitting frames are also described.

The mechanisms for allocating and deallocating a GTS are described. The deallocation process may result in the fragmentation of the GTS space, i.e., an unused slot or slots. The sub clause describes a mechanism to resolve fragmentation.

The MAC sub layer uses the mechanisms described for all incoming and outgoing frames.

Throughout this sub clause, 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 sub layer.

6.4.1. Channel access

This sub clause describes the mechanisms for accessing the physical radio channel.

6.4.1.1. Superframe structure

A coordinator on a PAN 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 $0 \leq SO \leq BO - 1$, $SD = aBaseSuperframeDuration * 2^{SO}$ 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.

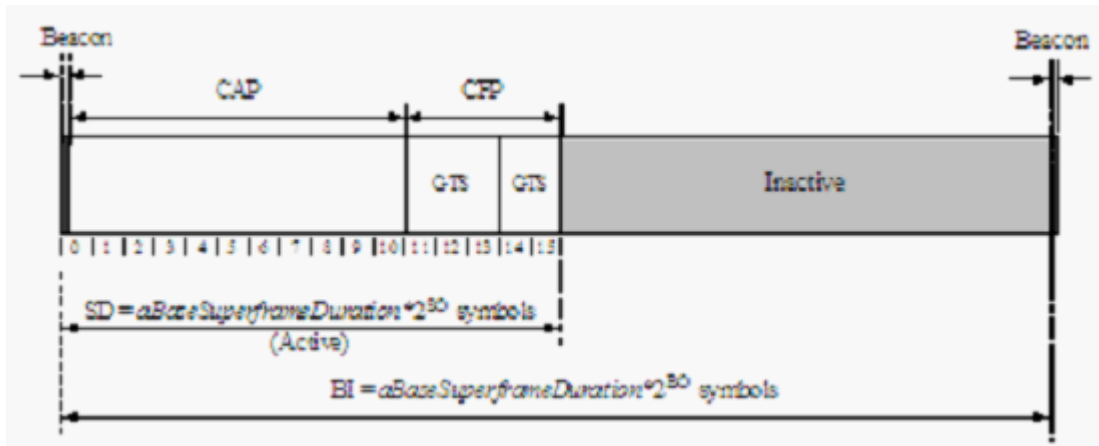
The active portion of each superframe shall be divided into *aNumSuperframeSlots* equally spaced slots of duration $2^{SO} * aBaseSlotDuration$ and is composed of three parts: a beacon, a CAP and a CFP. The beacon shall be transmitted, at the start of slot 0, and the CAP shall commence immediately following 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 GTSSs shall be located within the CFP.

The MAC sub layer shall ensure that the integrity of the superframe timing is maintained, e.g., compensating for clock drift error.

PANs that wish to use the superframe structure (referred to as a beacon-enabled PAN) 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.

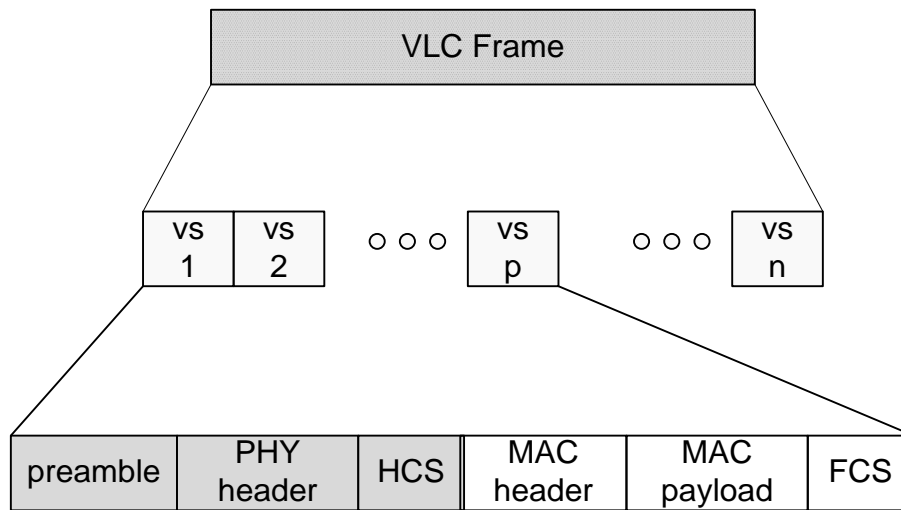
PANs that do not wish to use the superframe structure (referred to as a nonbeacon-enabled PAN) shall set both *macBeaconOrder* and *macSuperframeOrder* to 15. In this case, a coordinator shall not transmit beacons, except upon receipt of a beacon request command;. In addition, GTSs shall not be permitted.

An example of a superframe structure is shown below. In this case, the beacon interval, *BI*, is twice as long as the active superframe duration, *SD*, and the CFP contains two GTSs.

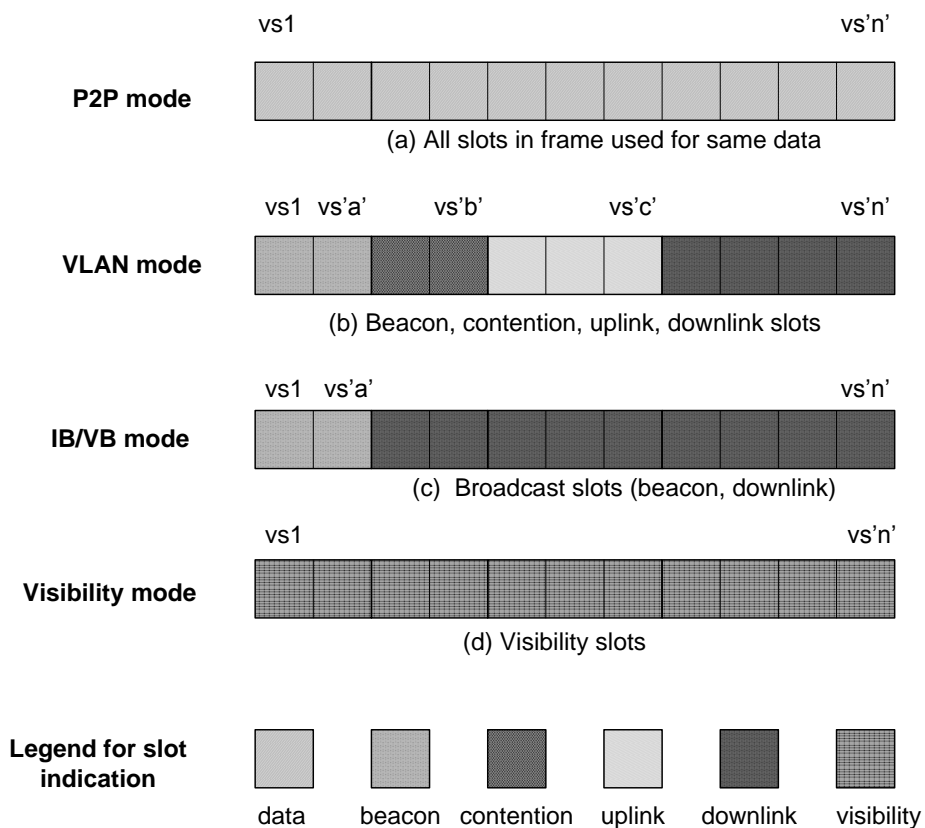


(Figure 54) Example of superframe structure

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. The number of slots in a VLC MAC frame is communicated in the MAC header. The standard defines the concept of a “virtual slot”, where the slot is defined and used differently in different VLC modes. This is shown in **Error! Reference source not found.55**. Communication between devices can take $1 \leq p \leq n$ slots, where ‘p’ is a positive integer and ‘n’ is the total number of slots in the frame. Thus, 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. The type of frame for the mode and the number of slots can be indicated in the MAC header. Transmission between two devices involves transmission of the preamble, the PHY header, the header check sequence (HCS) and then the MAC header and payload with a frame check sequence (FCS). The preamble is used for synchronization of the frames in the different modes.



(Figure 55) Single MAC frame structure for all VLC frames



(Figure 56) Usage of virtual slot concept for different MAC operating modes

The CAP and CPF slots are used in a flexible manner as shown in Figure 56. 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. Depending on the mode of operation, the virtual slots are programmed differently. For example, in Figure 56 (a), for P2P modes, all slots can be configured to transfer data between the two devices. In VLAN mode, as shown in Figure 56 (b), the first ‘a’ slots are used for beaconing from the infrastructure device to start timing and decide on how the slots are programmed for a given Mode. Slots (a+1) to b are for contention management for devices to join the access point. Slots (b+1) to slot (c) can be used for uplink access by the various devices that are associated with the access point. Slots (c+1) to ‘n’ can be used for downlink transmissions by the access point. In the IB or VB mode, all slots are again configured in the same direction (downlink) for broadcasting. Slots 1 to a are used for beaconing to indicate start of frame and which slots are actively used for broadcasting. The IB/VB modes can be formed by simply dropping the contention and uplink access parts of VLAN. Thus, the slot markers ‘a’, ‘b’, ‘c’ can take all values from ‘0’ to ‘n’ and thus, the slots can be programmed in a configurable manner for a given Mode. Figure 56 (d) shows the visibility mode where the slots are simply transmitting visibility patterns to assist with alignment for data transmission for uplink or to keep the infrastructure transmissions always “on” for downlink and to remove flicker. There is no MAC payload or FCS for visibility frames and a visibility pattern is sent for providing visibility. The reason to have a visibility frame and sending a PHY header and MAC header for the visibility pattern is to allow the receiving devices to ignore the pattern and go into power saving or hibernation states until the end of the frame. The visibility frame can also tell the receiver the actual pattern being sent which can be used for synchronization and for gain (channel) estimation and compensation. Although not explicitly mentioned, there may be a need for guard time between the different slot configuration changes to enable the transition from uplink to downlink and vice-versa. This may be as short as SIFS (short inter-frame spacing) that is commonly used to demarcate frame transitions in the MAC. Since the transmitter and receiver use independent circuitry for VLC, it is also possible that the guard time could be reduced significantly or even avoided, compared to other wireless systems that share the transmitter and receiver circuitry.

6.4.1.1.1. 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 and shall shrink or grow dynamically to accommodate the size of the CFP.

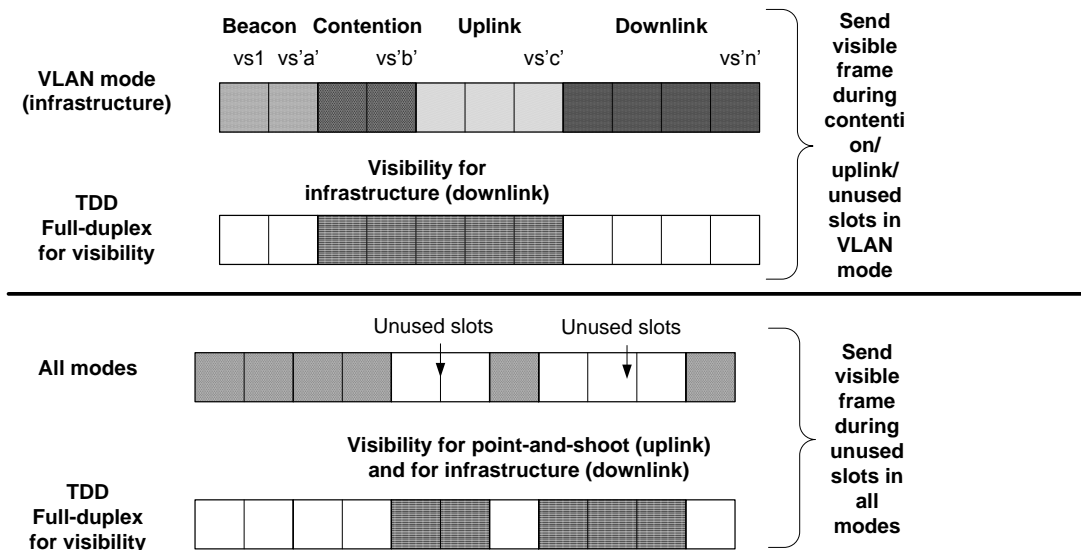
A device transmitting within the CAP shall ensure that its transaction is complete (i.e., including the reception of any acknowledgment) one IFS period before the end of the CAP. If this is not possible, the device shall defer its transmission until the CAP of the following superframe.

MAC command frames shall always be transmitted in the CAP.

6.4.1.1.2. 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 GTSSs have been allocated by the PAN 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 GTSSs. We will transmit uplink and downlink slots in the CFP period.

6.4.1.1.3. Visibility support during channel access



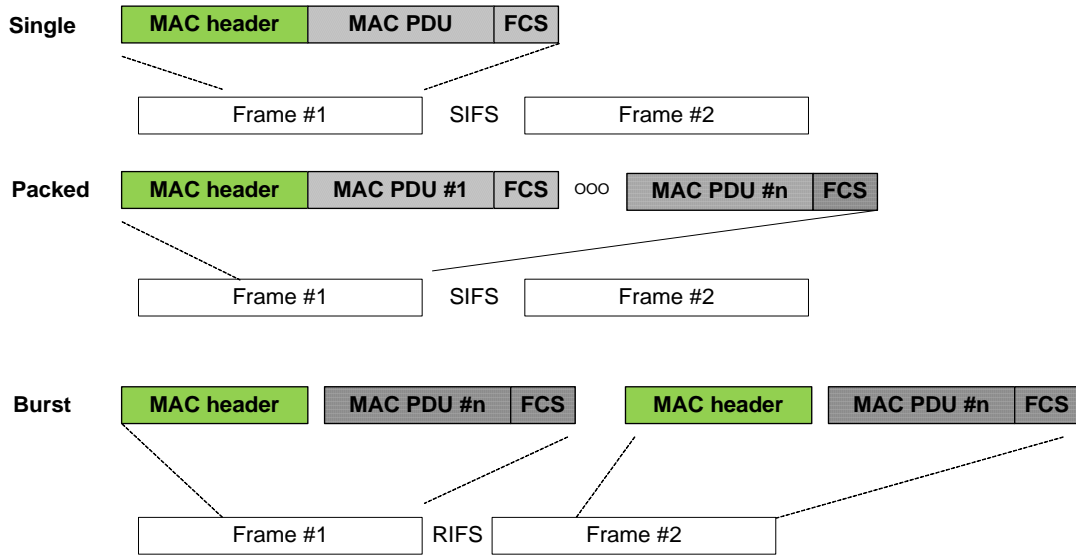
(Figure 57) Usage of visible frames during idle or RX modes of operation

The visibility slots can be used during contention and uplink slots in VLAN 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 57. 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.

6.4.1.2. 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 58) 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 5 3) 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

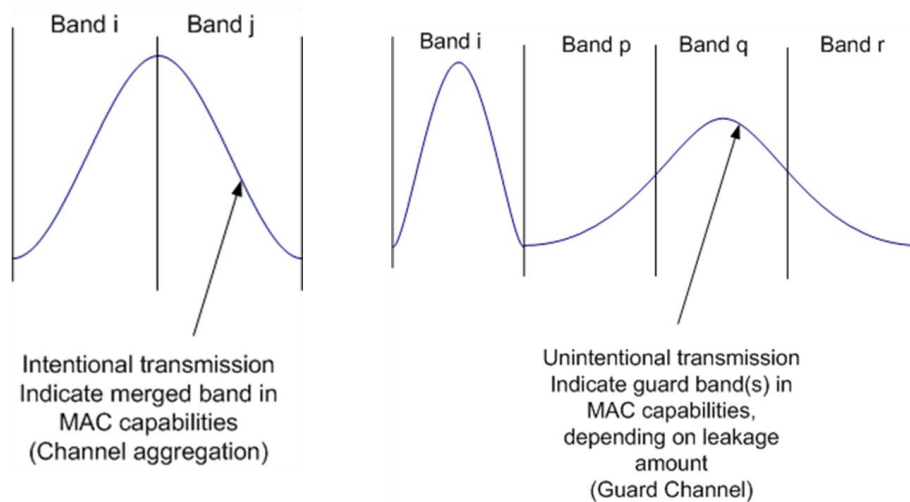
6.4.2. Starting and maintaining PANs

This sub clause specifies the procedures for scanning through channels, identifying PAN identifier conflicts, and starting PANs.

6.4.2.1. 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.



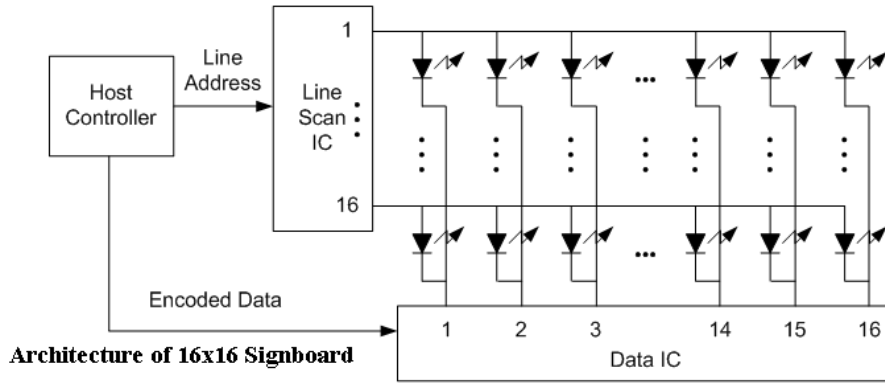
(Figure 59) Concept of aggregation channel and guard channel

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.

6.4.3. VLC TDM support for LED Signboard: Multiplexing

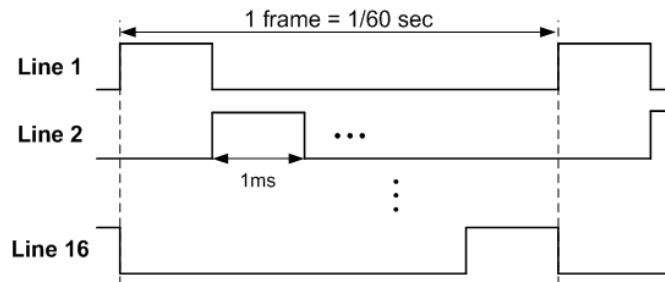
It consists with a host controller, line scan IC, Data IC and led matrix. Line scan IC selects a line for specific data stream and data IC transmit on/off or color selection information of each dot on the selected line. Line scan is active high, and data is active low. Line scan determines the operating time of each line.

Operating time means LED On time duration of selected line.



(Figure 60) Architecture of general LED signboard

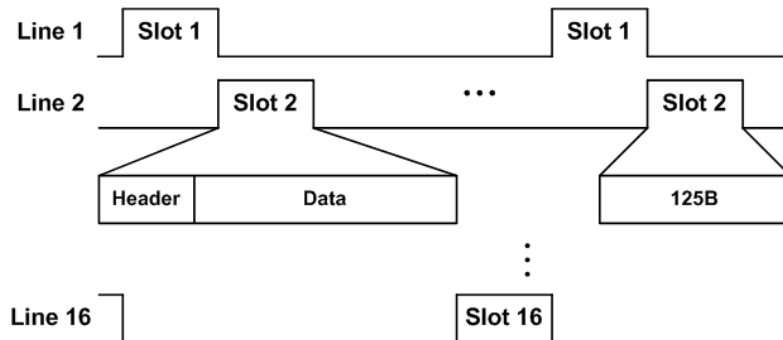
General PC monitor and TV transmit 60 frames per second. One frame is transmitted twice, it is same with transmission of 30 different frames per second. At LED signboard, frame transmission mechanism is similar to PC monitor and TV. 16 Lines have to operate 60 times during 1 second in case of 16 by 16 LED signboard. The operating time for 1 line is about 1ms: $(1s/60f)/16fp1 \approx 1ms/l$. At the signboard industry, generally 25 to 60 fps is used.



(Figure 61) Operation of 16x16 Signboard

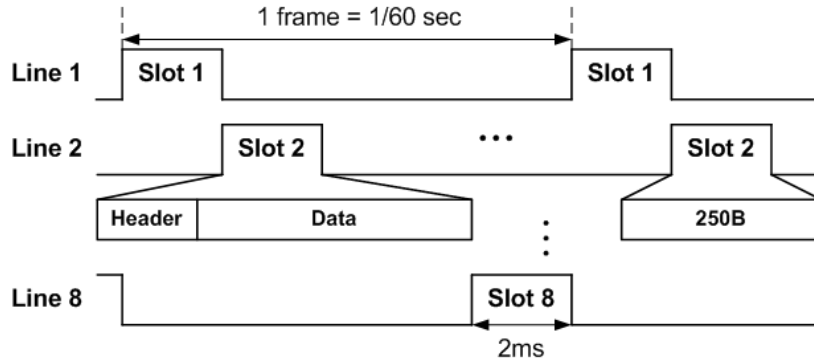
Line operating time 1ms is fixed at one signboard. So, we can arrange 1 ms for 1 time slot.

16 time slots are possible. For example, if we consider 1Mbps, 1 time slot can transmit 125bytes.



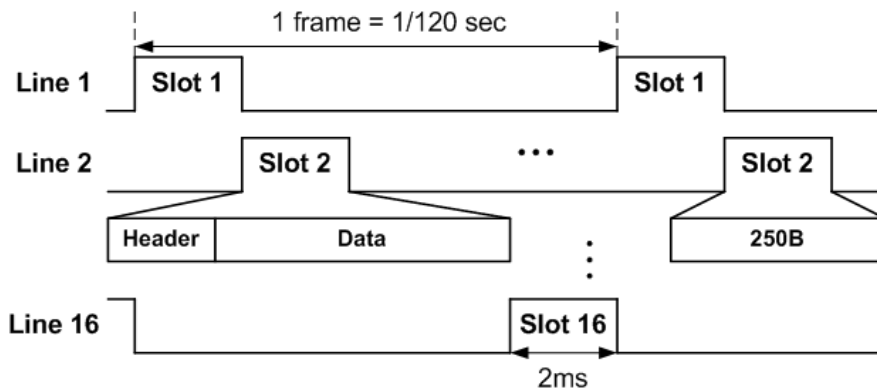
(Figure 62) TDM for Signboard

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 63) 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 64) 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.

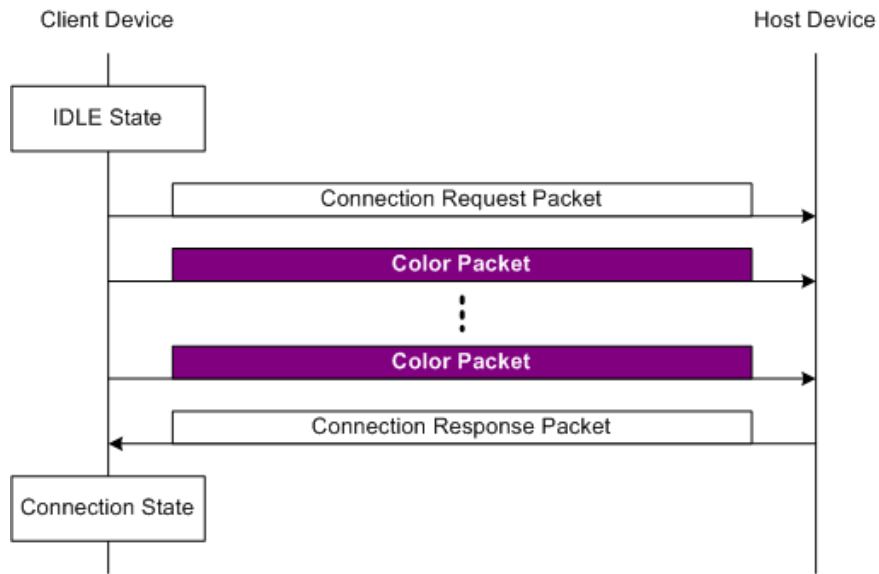
6.4.4. Visual link establishment with Color Packet Scheme

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.

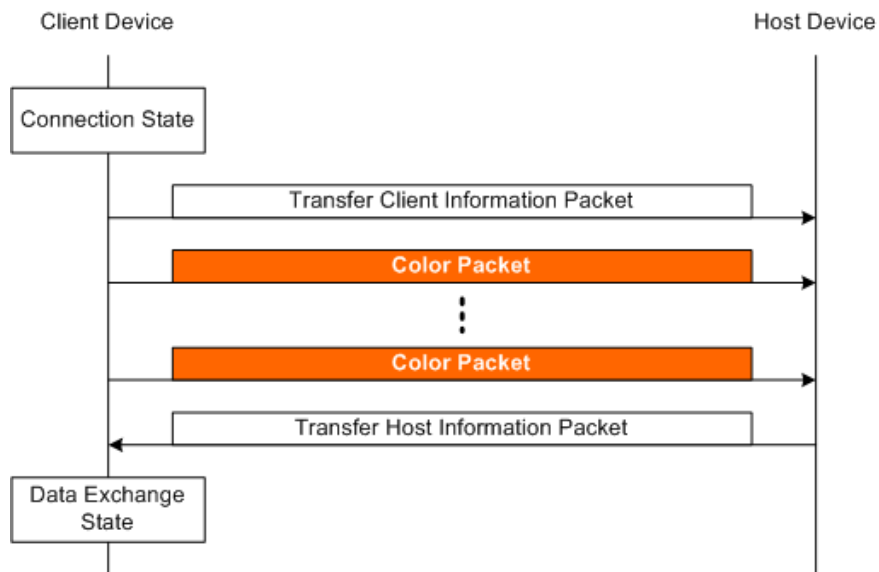
When we use Color Packet in VLC, we can supply information to user intuitively and transfer messages to peer device. For examples, in communication between application and user, we can directly see the status information such as current step of communication procedure, data transmission quality (PER, 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.



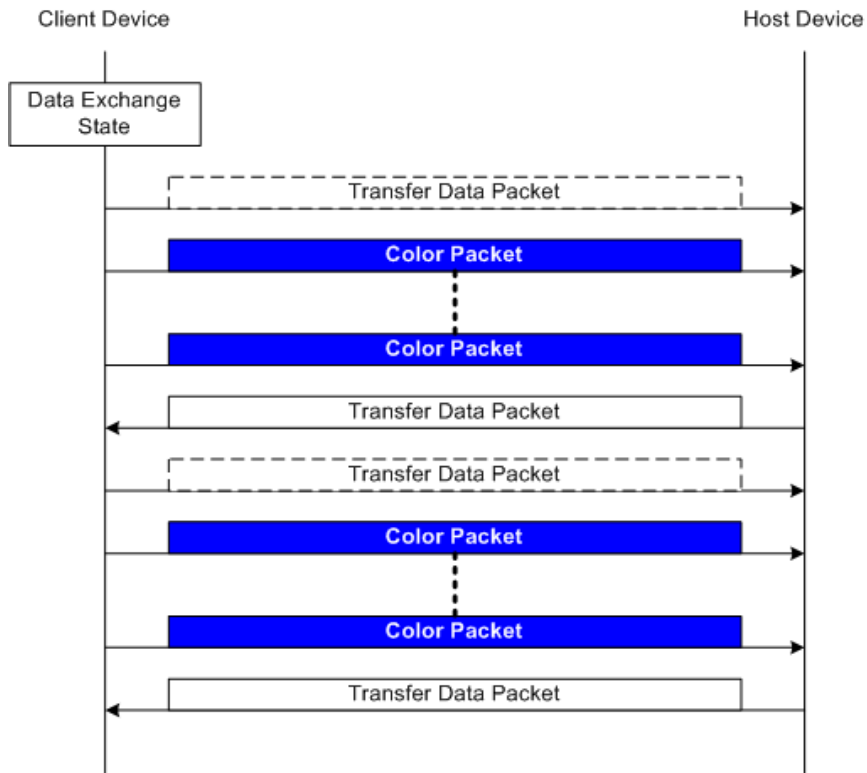
(Figure 65) Step1 – A Color Packet Usage for Connection procedure

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.



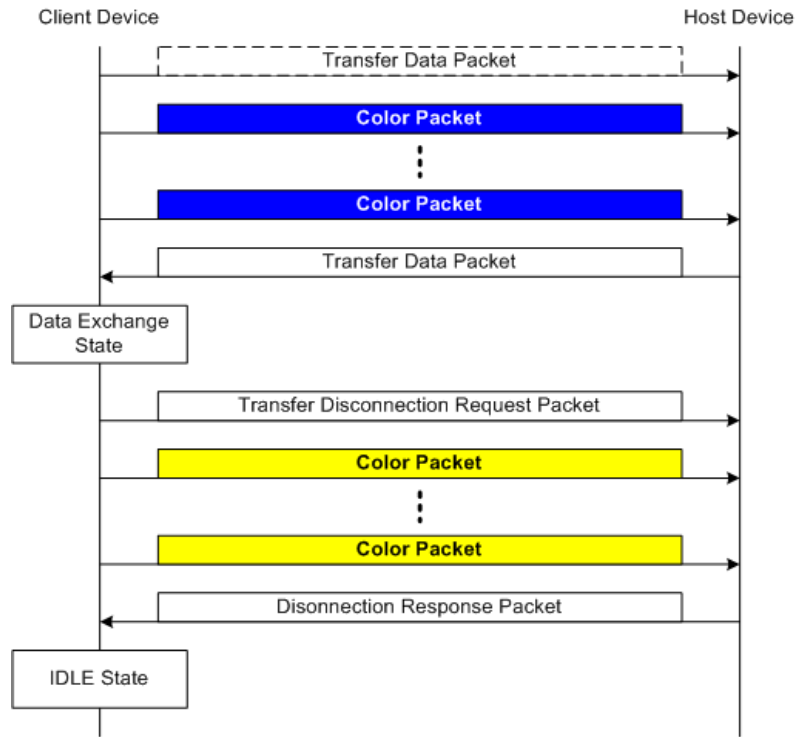
(Figure 66) Step 2 – A Color Packet Usage for Exchange Information Procedure

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.



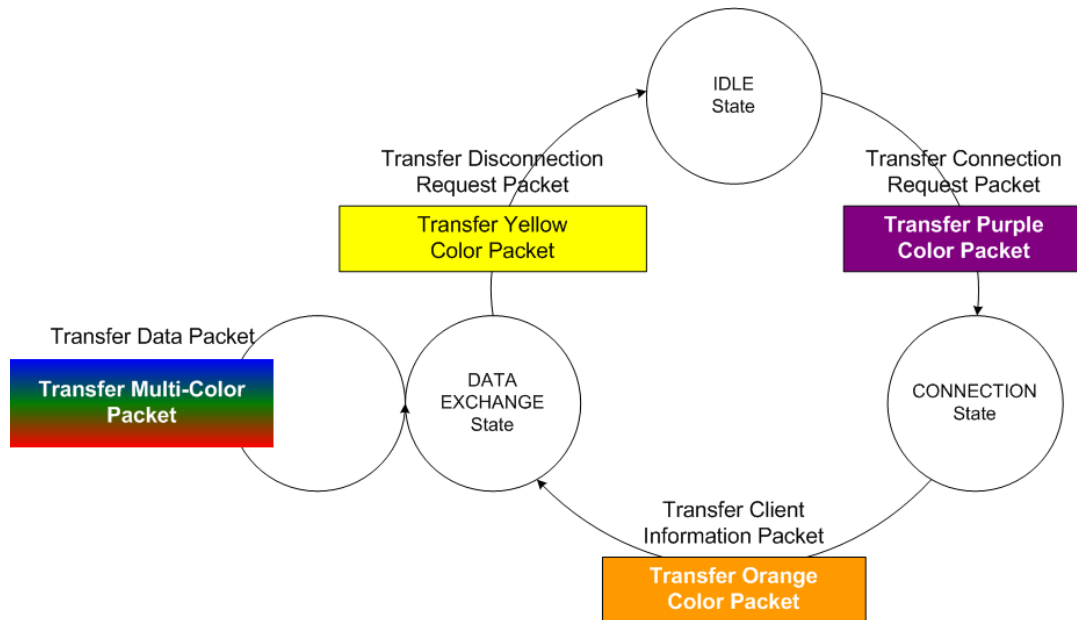
(Figure 67) Step 3 – A Color Packet Usage for Transfer Data Procedure

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 68) Step 4 – A Color Packet Usage for Transfer Disconnection Procedure

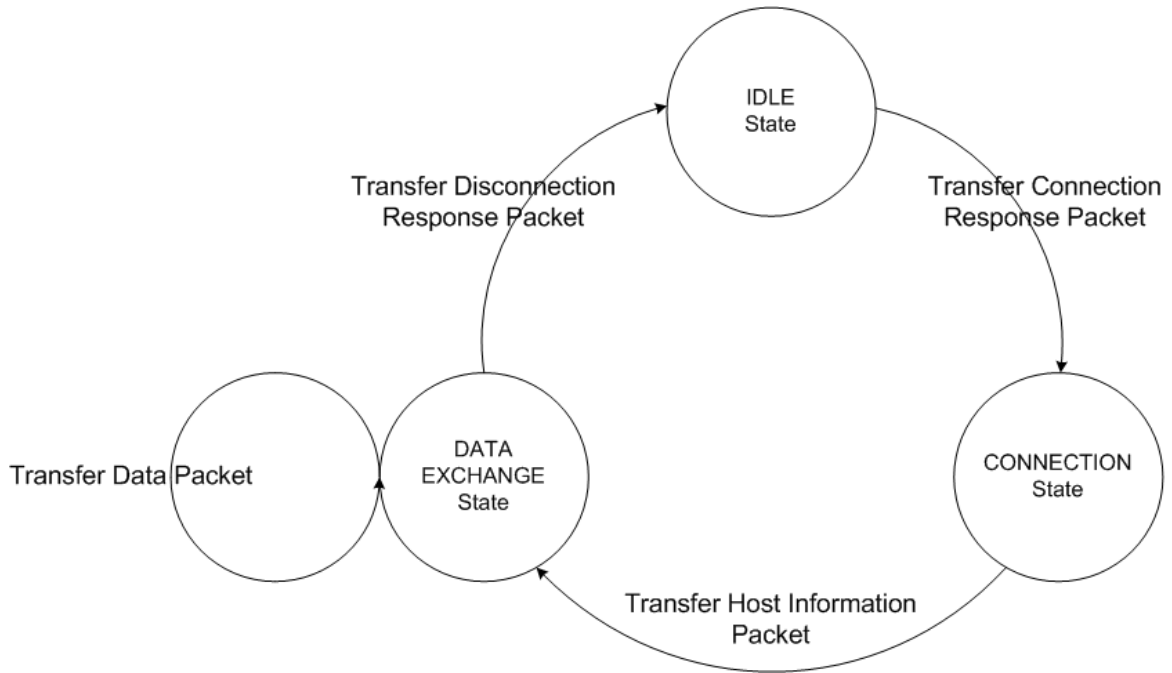
At last step, client device state transit from data exchange state to IDLE state. Client device transfer Yellow Color packet to host device during state transition. User can know the current step of communication procedure by using Color Packet during these communication procedures.



(Figure 69) Color Packet Client State Diagram

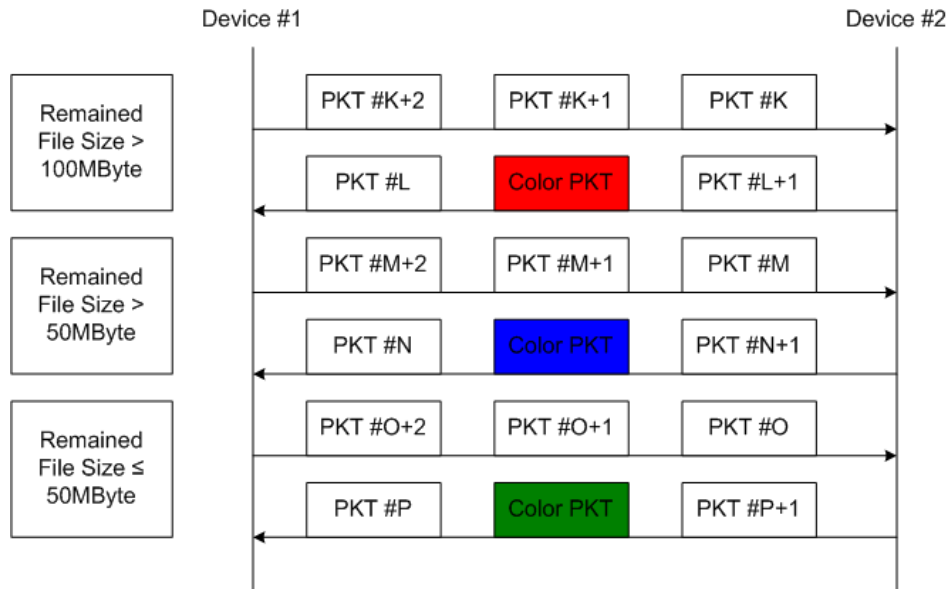
This slide shows Client State Diagram in Previous Basic Communication Procedures. Each

color packet is transferred during each state transition.



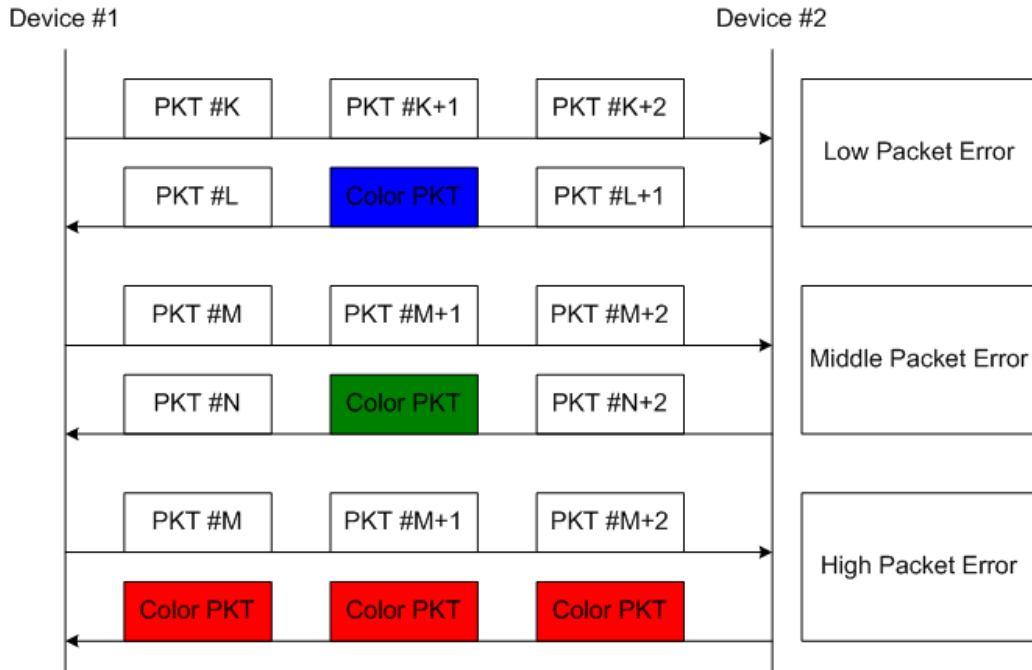
(Figure 70) Color Packet Host State Diagram

In case of asymmetric data transfer, host doesn't transfer color packet to client for the transmission of data packet.



(Figure 71) 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 72) 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 5 4) 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.



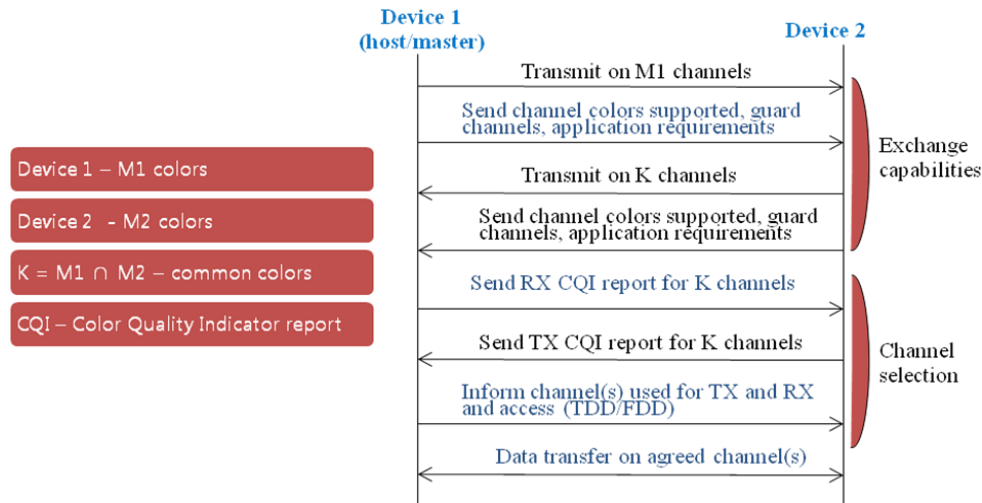
(Figure 73) Color packet

6.4.4.1. 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.

6.4.5. Starting a PAN



(Figure 74) 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 M_1 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 $1 \leq x \leq K$, 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 $1 \leq y \leq K$, 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 VLAN 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.

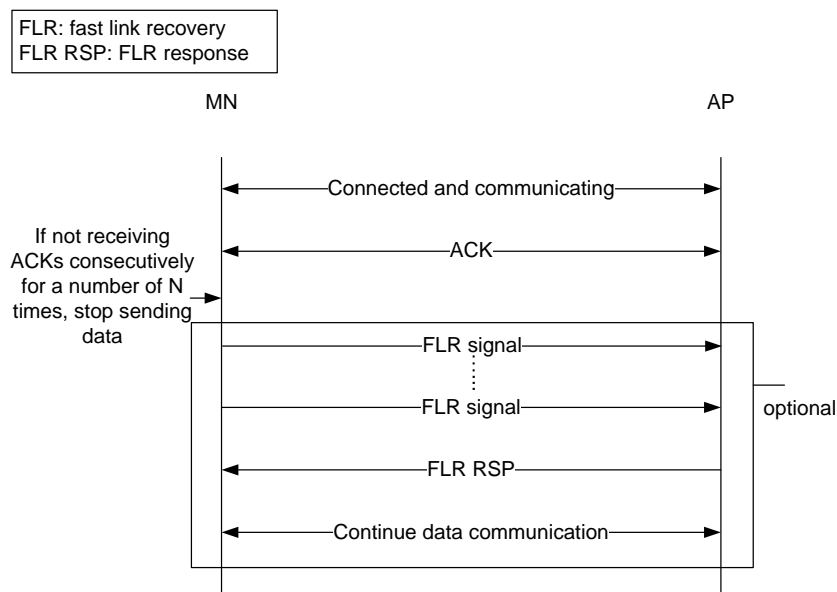
Starting a PAN is only applicable to bi-directional communication modes.

6.4.6. Fast link recovery

In VLAN, 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.

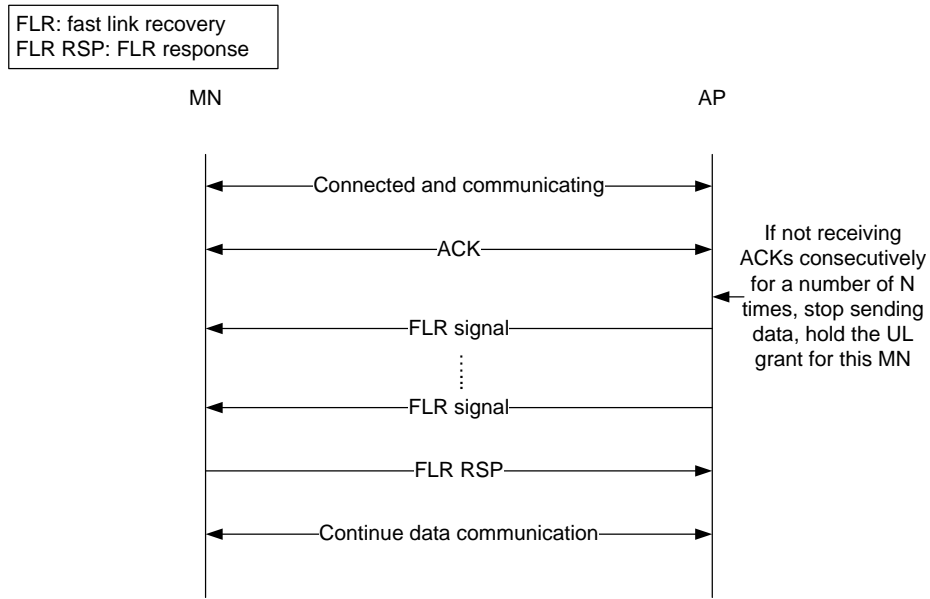
Figure below shows an example of the process of MN stopping sending data based on the retransmission count.



(Figure 75) An example of the process of MN stopping data transmission based on the retransmission count, and triggering FLR.

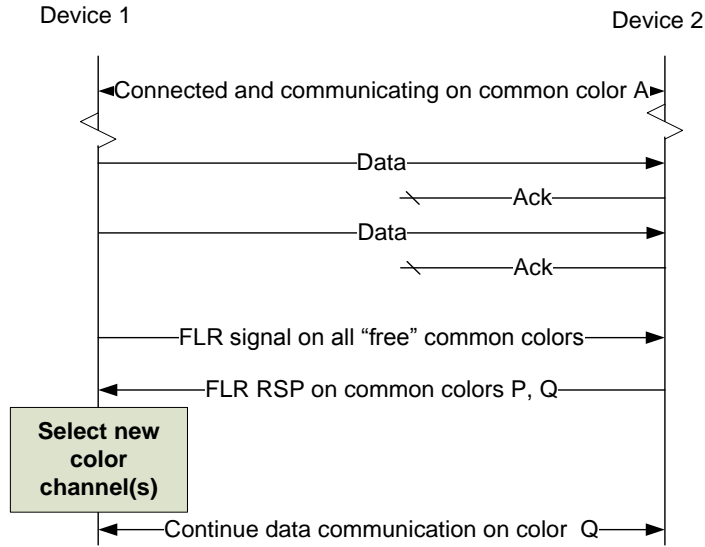
In VLAN, a fast link recovery may be triggered at the access point (AP) in the visible light communication. The trigger can be that the AP does not receive contiguous ACKs for a number of times given by a parameter `N_ACKS`. In the fast link recovery process, the AP may stop sending data to the MN. The 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.



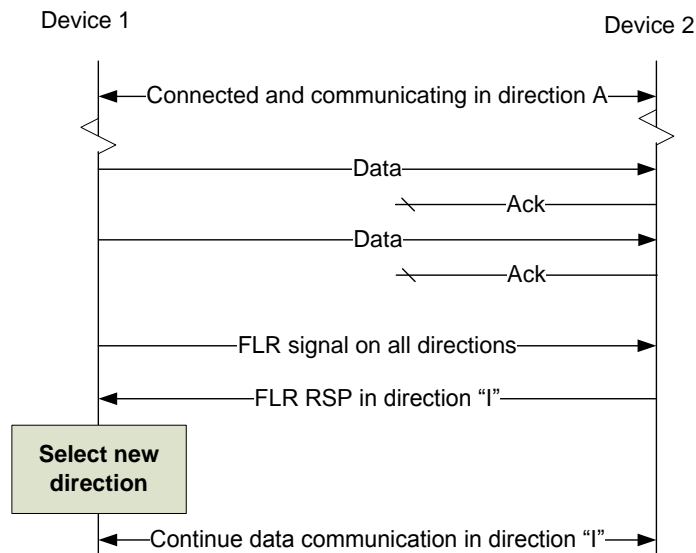
(Figure 76) An example of the process of AP stopping sending data based on the retransmission count, and triggering FLR.

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 77) 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.



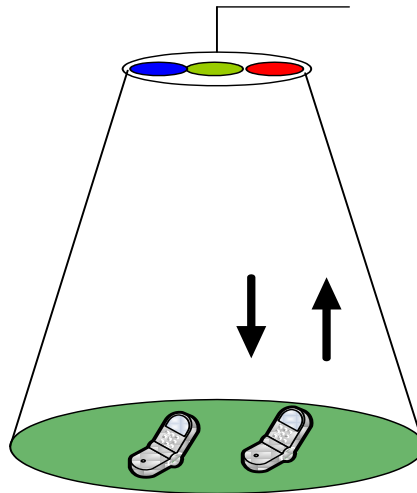
(Figure 78) Flowchart showing process of multiple angles assisted fast link recovery

6.5. Multiple channel resource assignment

In order to support system capacity enhancement and multiuser communication, VLC system can apply multi channel application. This channel can be assigned to one user and multi user based VLC.

6.5.1. Multiple channel information

If AP(Access point) uses this multi channel application in VLC system, MS(Mobile Station) can be received Src_multi_info. This information is to notify about AP multiple channel service. If AP do not use multiple channel service, bit '000' 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

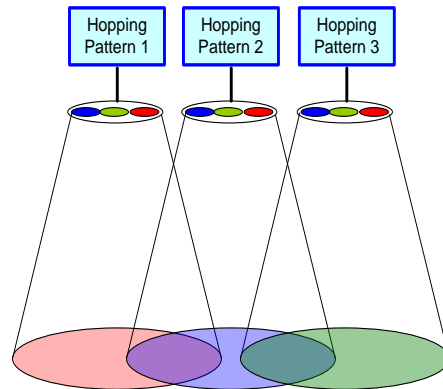


(Figure 79) Channel assignment of MS information

6.5.2. Channel hopping for interference avoidance

6.5.2.1. Hopping pattern information

This scheme will be used to avoid interference of other user. In order to avoid other user interference, AP assign 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 some frame or some time slot based.

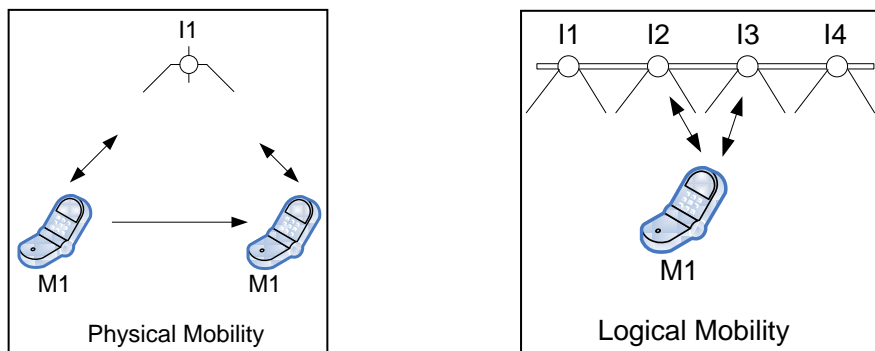


(Figure 80) Hopping pattern assignment

Figure 2 shows hopping pattern assignment in multiple channels. Table 2 expressed hopping pattern example for applicable to VLC. If AP assign pattern ‘001’ 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

6.6. Concept of VLC cell and mobility

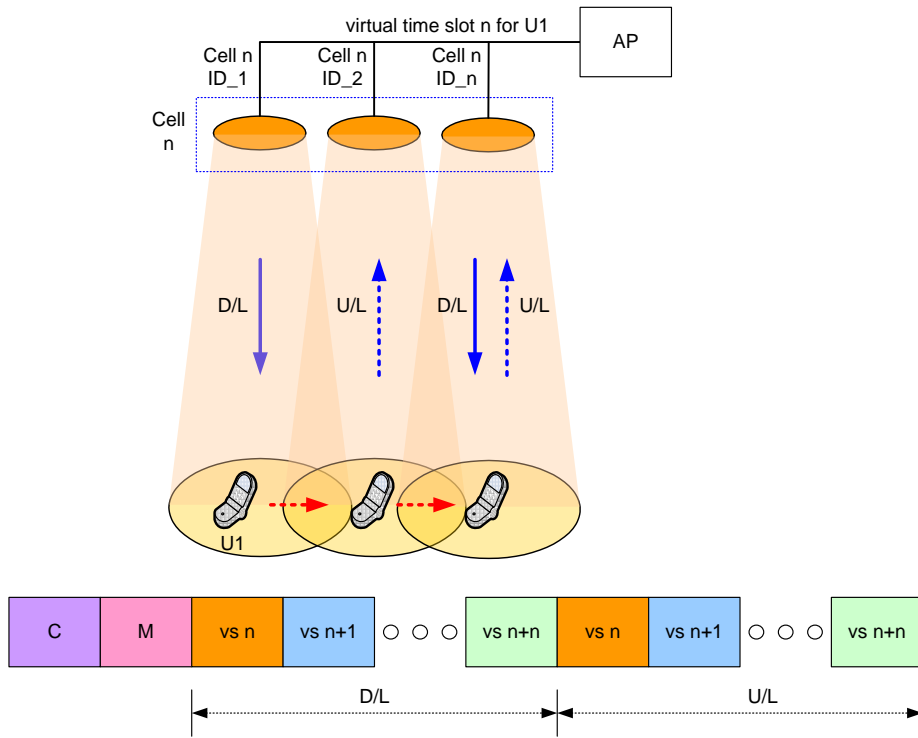
There may be a need to support link switching due to physical movement or interference. Mobility can be of two types: physical and logical. Physical mobility occurs when the VLC device M1 changes its position due to the movement within the coverage area of infrastructure I1 while logical mobility occurs 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 81) Physical and logical mobility

6.6.1. Physical mobility:

Sometimes, illumination or many LED Tx do not need to send data through whole LEDs when space is so big and there are not many receivers. To reduce power consumption in Tx side, some section of LEDs send data where Rx exists. And to support mobility, spatial mobility can be supported. When Rx does not move, small section of LEDs sends data. If Rx moves, then Tx side can receive NACK through the PD which is at the outside reserved section. Reserved section transmits data through the LED. And then Tx expands LED section to find receiver. If Tx receives ACK through the PD then LED section will be reduced because Tx knows where Rx is. If Tx cannot find where Rx is, then Tx stop to find Rx. And next AP will try to find where Rx is.



(Figure 82) VLC mobility

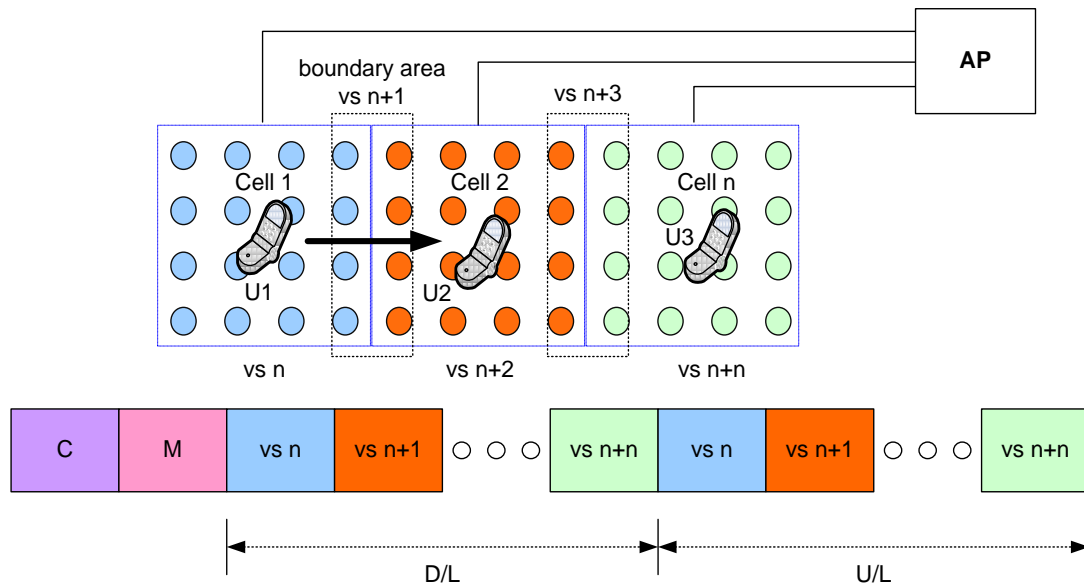
In VLC communication system, each optical source has a function of transmitter(like as LED/LD) and receiver(like as photo detector). In order to support MS mobility in VLC system, VLC system of cell based configuration can be defined as communication system. Figure 1 shows one of the VLC system cell configurations. A VLC cell definition can be designed as some optical source groups. A cell definition is granular group of each VLC optical source.

Also each optical source has each cell ID like as Figure 82. For MS mobility support in VLC, large cell size of optical source group 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 in aspect of system capacity.

In Figure 82, some optical source was grouped as a cell area. Each optical source has function of transmitter(like as LED/LD) and receiver(like as photo detector). If we assumes that U1(user 1) moves to next optical source area 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 AP transmit U/L signal(like as data ack or response) to optical source. Then MS mobility can be possible in VLC communication system.

- Resource assignment in mobility



(Figure 83) 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 during U1 and AP communication, 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. 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 of AP can assign new virtual time slot vs. n+1 to U1 simultaneously. Time slot resource vs. n+1 will not use in cell 1 and cell 2 for cell interference problem. 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, MS can discriminate that what is cell 1 optical source alarm and cell 2 optical source alarm because boundary area optical source of cell 1 edge and cell 2 edge transmit B_info, and S_info, MS ID, Cell_info simultaneously.

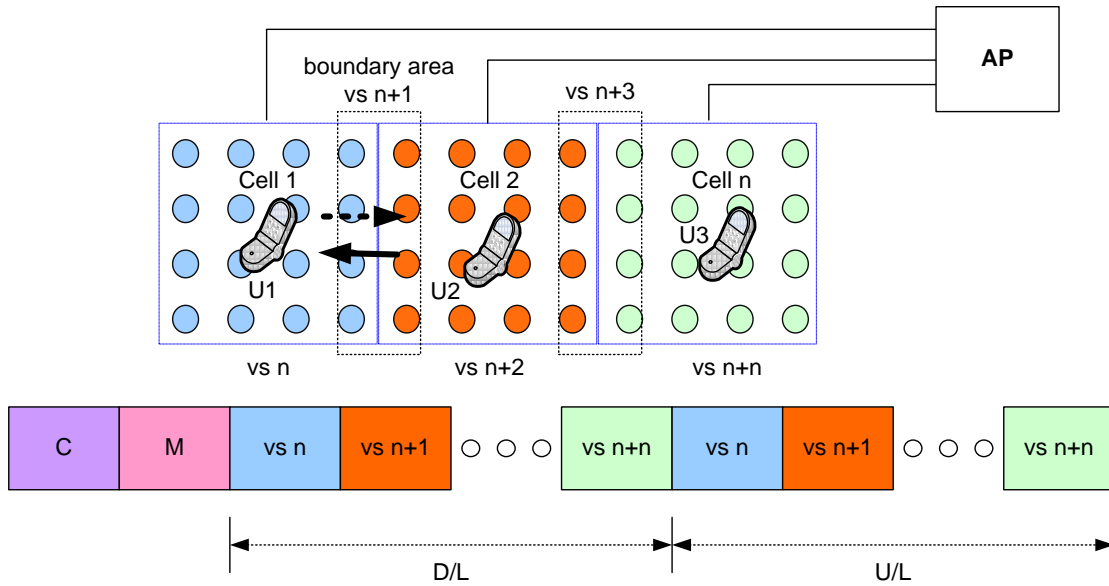
If U1 continues movement from boundary area to cell 2, then U1 can detect cell 2 optical source alarm in boundary area. In this case, U1 will return previous time slot resource vs. n automatically,

because time slot vs n resource was assigned in cell 1. this return action will give a chance to resource assignment of other MS without previous time slot return notification of AP.

If U1 reaches in cell 2, U1 will communicate with AP by using vs n+1 only.

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.

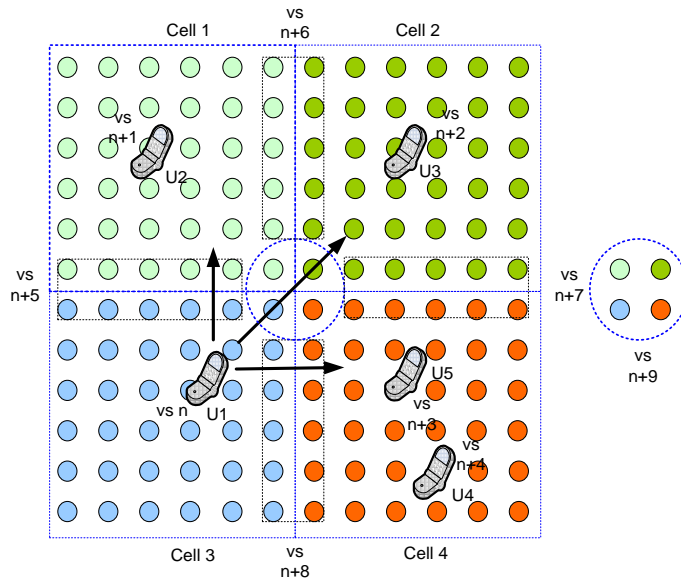
The other automatic return action of previous time slot resource vs n is that U1 do not detect boundary alarm information in cell 2. Its return action depends on boundary alarm information detection in U1



(Figure 84) VLC resource assignment

Figure 84 shows that U1 was returned to previous cell 1 after vs n+1 time resource assignment from AP. This case is the same Figure 2-1. When U1 didn't detect boundary alarm information or When U1 detect optical source ID of boundary area was changed after returning cell 1 from boundary cell, U1 will return vs n.

- Resource assignment in multi cell overlapped edge area



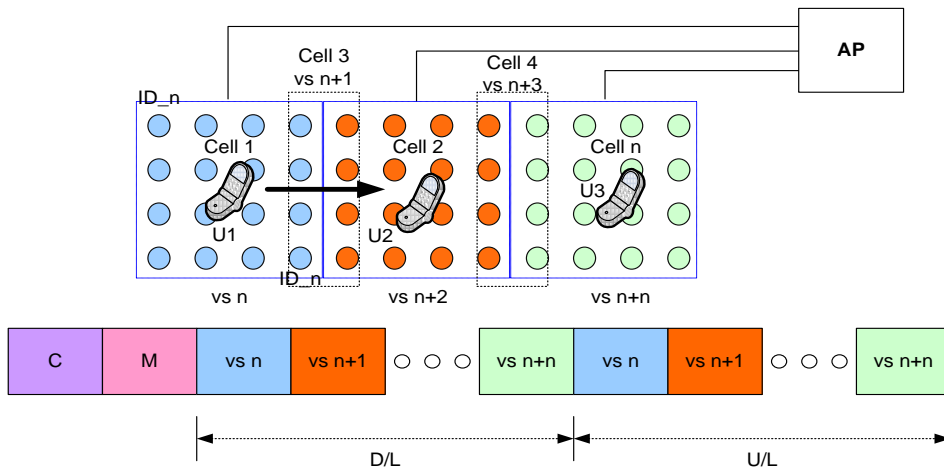
(Figure 85) Multi cell overlapped edge resource assignment

In Figure 85, U1 movement from cell 3 to cell 1 and cell 4 is the same as Figure 82.

If U1 want to move cell 2 area, then 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 optical source will assign time slot vs n+9. U1 will uses vs n and vs n+9 time slot in multi cell boundary. But vs n+9 time resource cannot be used cell 1 and cell 2, 3, 4 in order to avoid cell interference

6.6.2. Same optical source ID assignment in a cell

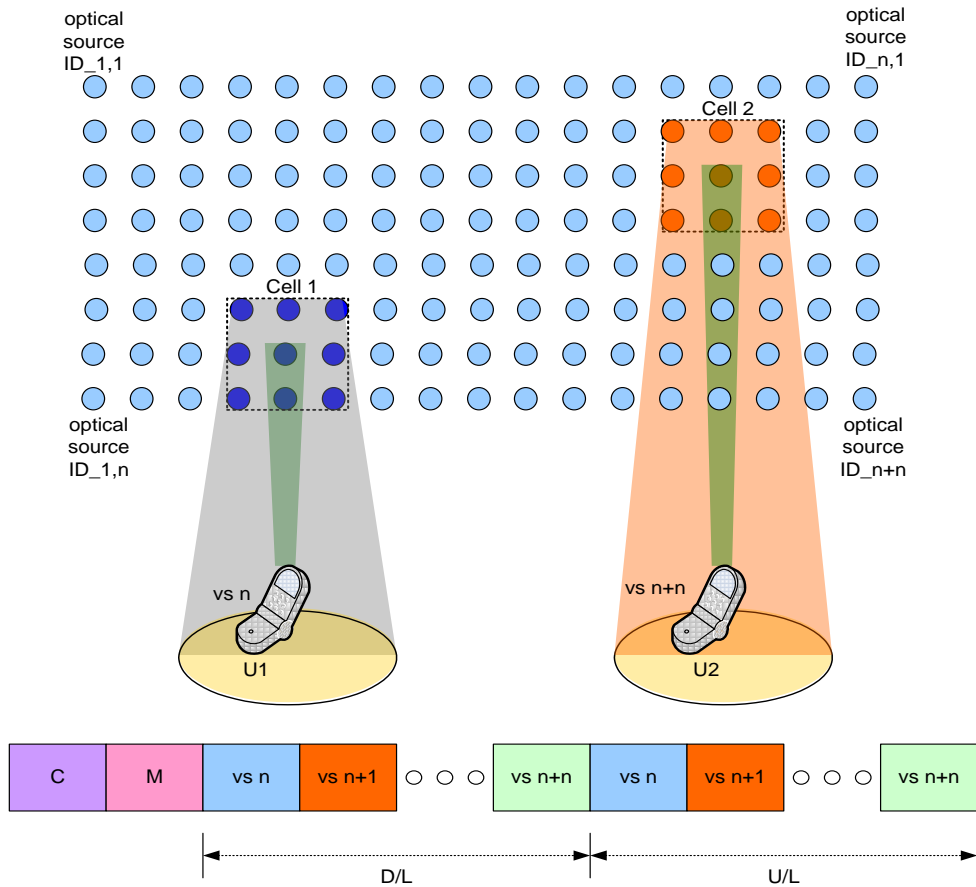


(Figure 86) Same optical source ID assignment

Figure 86 shows same optical source ID assignment in a cell. But different cell ID in boundary area can be assigned for mobility. In this case optical source cannot detect U1 movement position because the same optical source ID was used in a cell.

If we are supposing that U1 moves from cell 1 to cell 2 with U1 communication, then U1 must pass boundary area. Though optical source cannot detect U1 movement, when U1 reaches boundary area, then optical source can detect U1 movement because cell 1 and boundary area are different optical source ID. Also all optical sources in a cell use the same optical source ID and all optical sources in a boundary area use the same optical source ID but cell area and boundary area are using different ID.

6.6.3. Fractional resource assignment



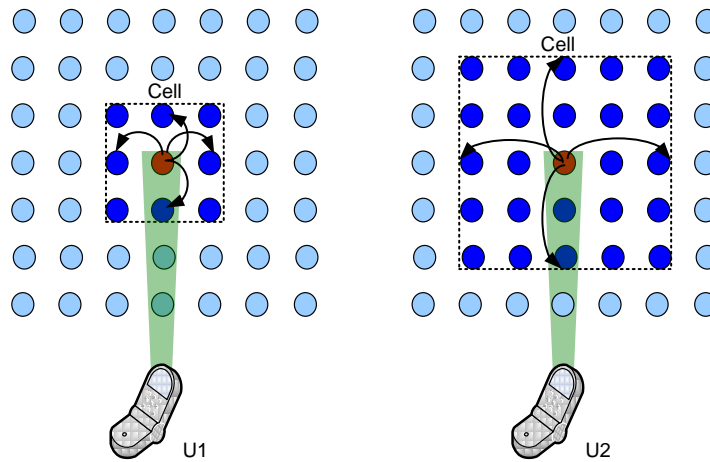
(Figure 87) Fractional resource assignment

This VLC system 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 5. In this case all optical sources has optical source ID. If U1 transmits initial access, receiver 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 define a certain cell area configuration for U1. Other area of full cell can be assign time slot and cell area for other user service. It will increase system efficiency.

6.6.4. Granular cell configuration and resource assignment

This is used for cell size definition and can support active cell mobility. In figure 87, cell size can be defined by using G_cell_ID. If G_cell_ID is set as 0000 0001, then AP makes a cell right, left, top and bottom direction of 1 optical source based on the strong optical power receiver in Figure 87. In figure 88 gives an example for G_cell_ID (0001 and 0010) cell definition

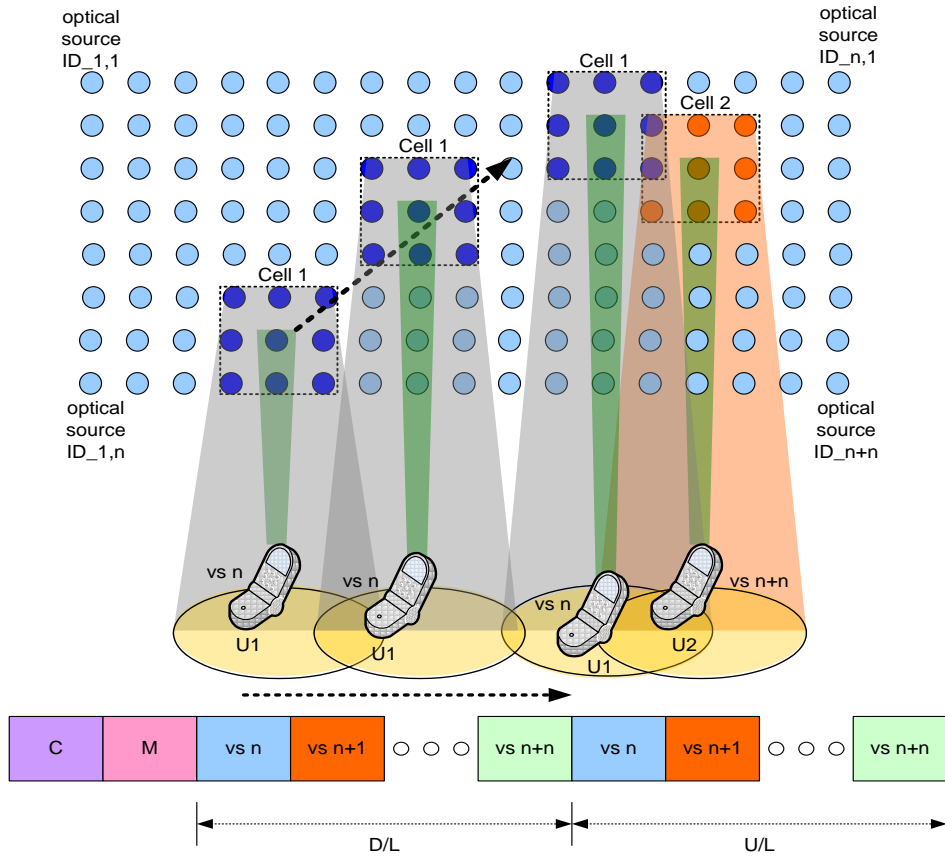


(Figure 88) cell definition by using G_cell_ID

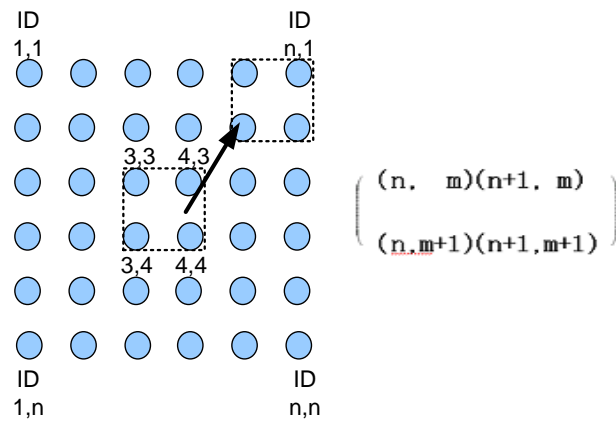
6.6.5. Granular cell resource assignment for mobility

Figure 89 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.

In Figure 90 shows optical source ID assignment. AP has these ID position. If MS moves optical source, AP compare MS position based on MS uplink signal. If MS has movement, then AP changes cell window according to MS movement direction



(Figure 89) Resource assignment for granular cell



(Figure 90) Optical source ID assignment

7. Visibility support

7.1. Necessity

The standard supports visibility for the following purposes:

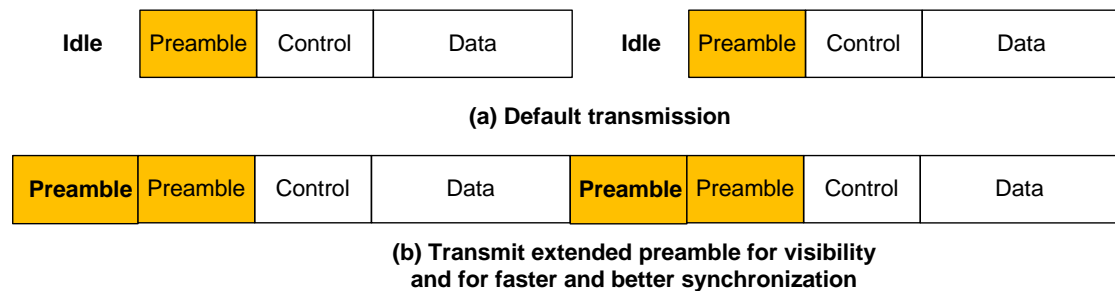
- Alignment (Device discovery, negotiation, connection)
- Visible guiding for user alignment
- Infrastructure continuous light output
- Blinking for unexpected interference, disconnection warnings

7.2. 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.

7.3. 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.

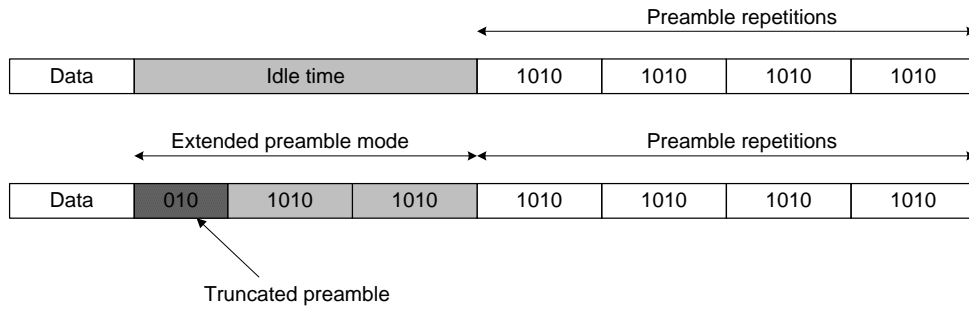


(Figure 91) Extended preamble mode provided by the MAC

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.

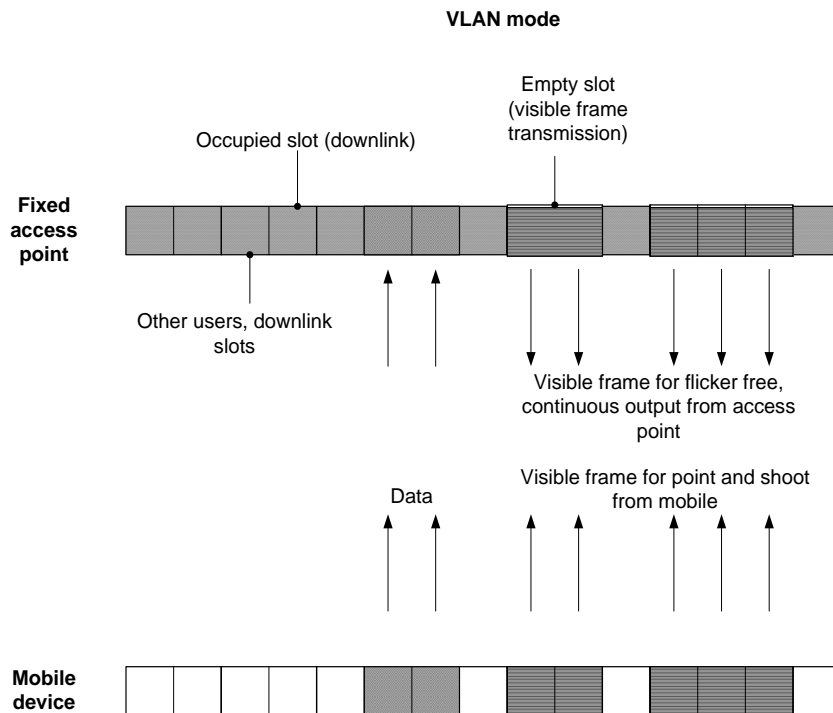
Preamble pattern 1010 is shown as an example preamble. Since idle time is not an integral multiple of the preamble, only a fraction of the preamble pattern such as ‘010’ can be sent to complete the idle time.



(Figure 92) Truncated preamble in extended preamble mode for utilizing idle time for visibility

7.4. Transmitting visibility pattern during uplink for VLAN mode

For the VLAN 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.

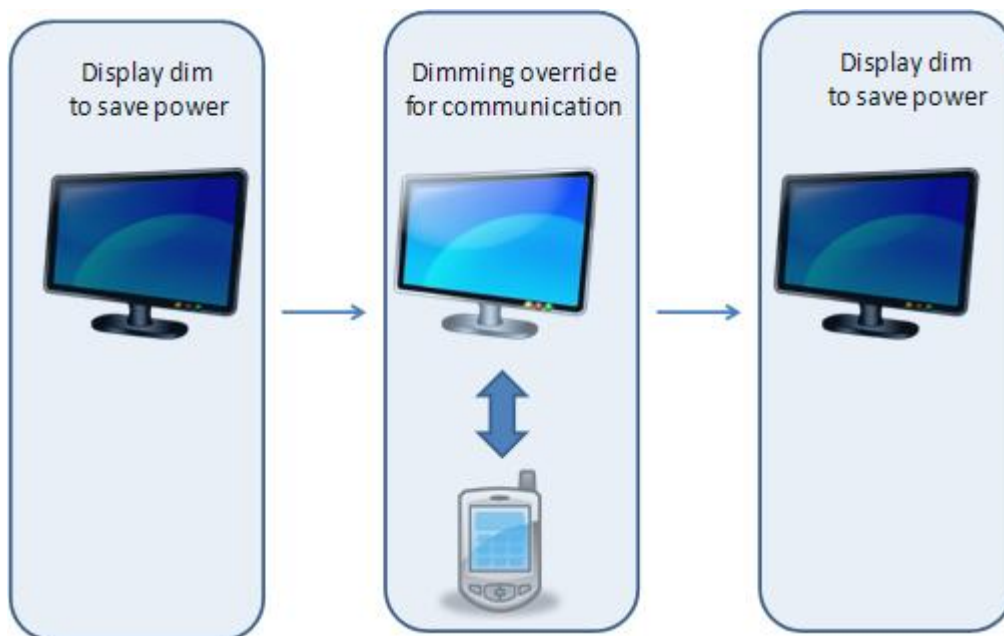


(Figure 93) Usage of visible frames during VLAN operation

8. 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)

8.1. Dimming override capability



(Figure 94) 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.

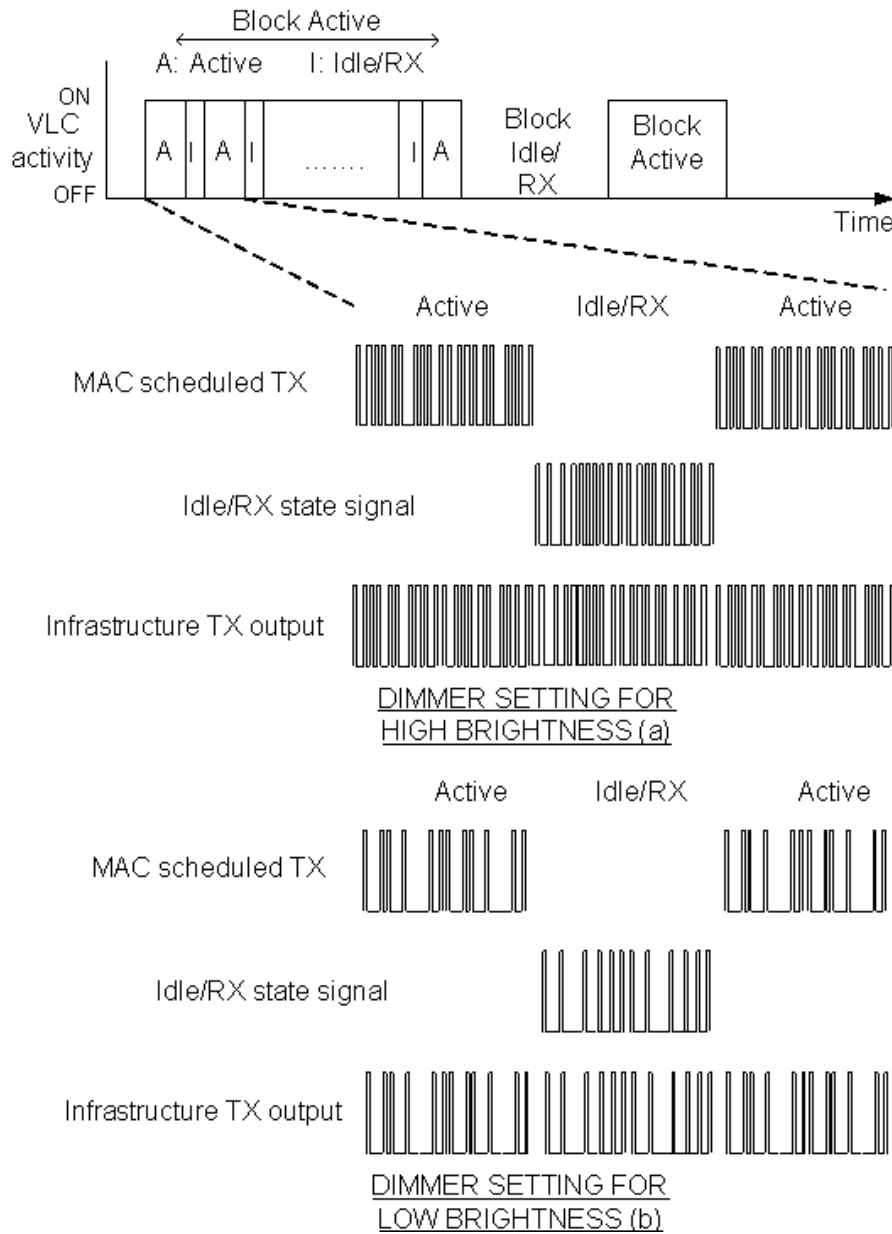
A dimmer override capability signal is added to the MLME SAP and provided to the external dimmer interface. This dimmer override signal shall be set to '1' by the MAC during VLC operation and shall be set to '0' after the communication has been completed. The usage of this dimmer override signal by the

external dimmer circuit is out-of-scope.

8.2. 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).

8.3. Supporting visibility pattern depending on dimming levels

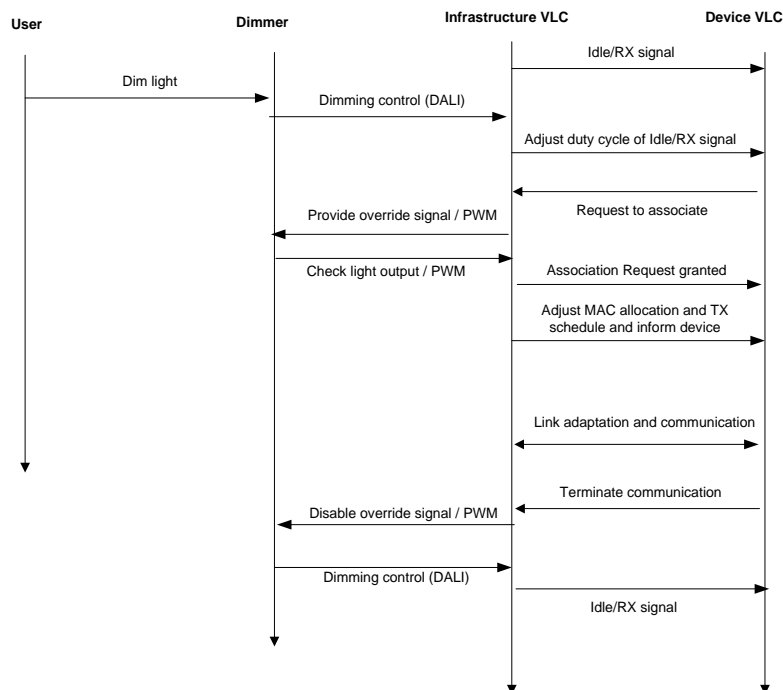


(Figure 95) Adapting dimmer pattern and data duty cycle depending on dimmer setting

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.

8.4. MAC layer transmission adjustment for dimming



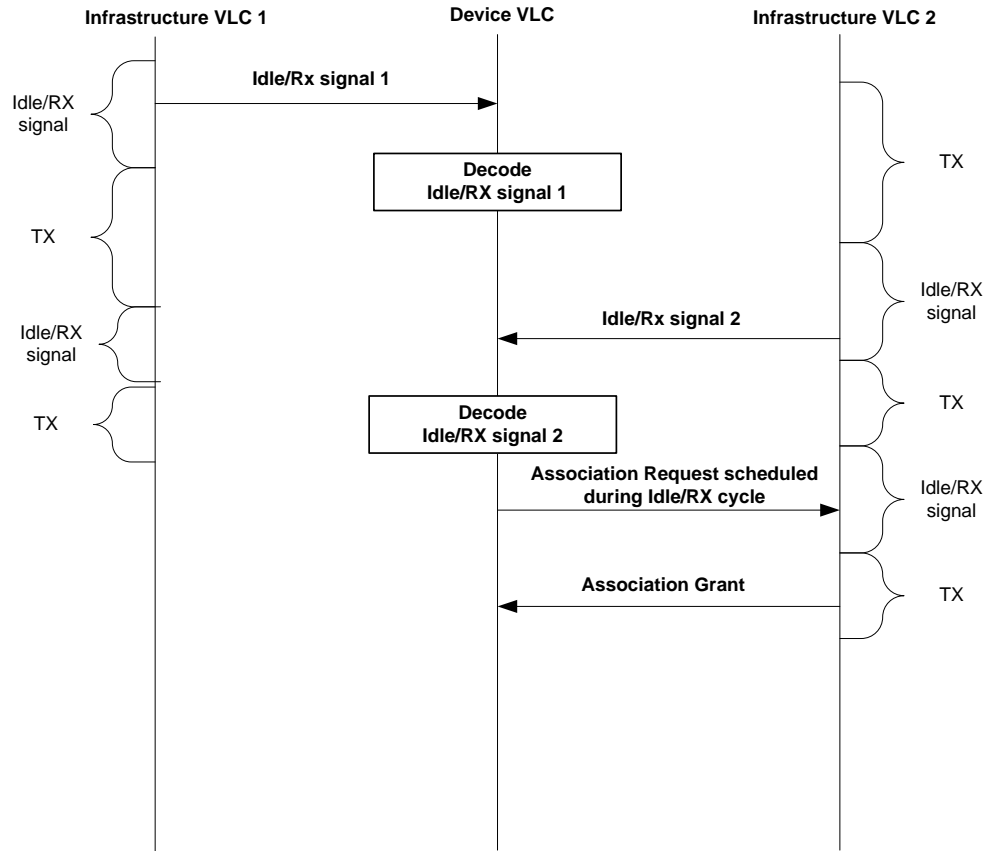
(Figure 96) Usage of MAC layer to adjust duty cycle to meet dimming requirements

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.

8.5. 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

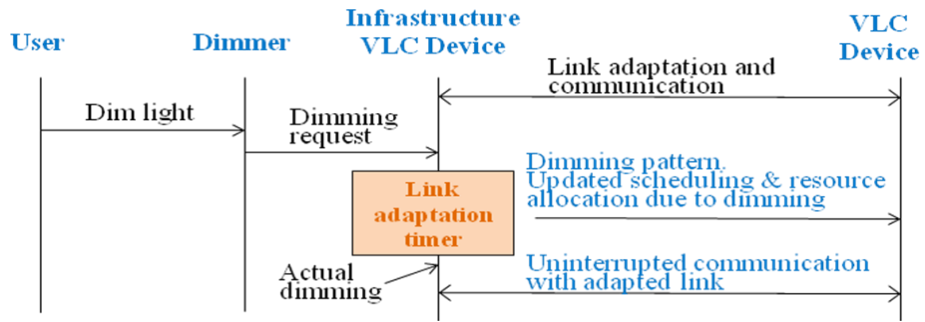
on the dimming pattern change and duty cycle, the VLC receiver may choose to select a different infrastructure that is currently not being dimmed or has a higher duty cycle (more illumination).



(Figure 97) Using dimming pattern as signal to establish link to best infrastructure device

8.6. 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 98) Usage of MAC layer to delay dimming and adapt resources for uninterrupted link