IEEE P802.15

Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)
Title	Narrow Band Frequency Hopping PHY Proposal for 802.15.4g
Date Submitted	30 April 2009
Source[1]	[Michael Schmidt] E-mail: [michael.schmidt@atmel.com] [Dietmar Eggert] E-mail: [dietmar.eggert@atmel.com] [Jeritt Kent] E-mail: [Jeritt.Kent@analog.com] [Cristina Seibert] E-mail: [cseibert@silverspringnet.com] [George Flammer] E-mail: [gflammer@silverspringnet.com]
Re:	[]
Abstract	[Detailed Proposal for a Narrow Band Frequency Hopping PHY for 802.15.4g]
Purpose	[Technical Proposal]
Notice	This document has been prepared to assist the IEEE P802.15. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein.
Release	The contributor acknowledges and accepts that this contribution becomes the property of IEEE and may be made publicly available by P802.15.

---

[1] *Note: sources listed are in no particular order.*

Proposed Narrow Band Frequency Hopping PHY Specification for Smart Utility Networks (SUN)

Submitted to IEEE 802.15.4g

Abstract

The purpose of this document is to provide the specifications for a Narrow Band PHY optimized for Frequency Hopping (NBFH PHY). This proposal is to be submitted to the Smart Utility Networks (802.15.4g) Task Group for consideration in the PHY Amendment specification. The document is structured to follow the existing 802.15.4 standard. The term "PHY" in this document refers to this proposed NBFH PHY.

Contents

Tables

Figures

1. Overview

1.1 General

Smart Utility Networks (SUN) are large scale networks formed by simple, low cost devices, typically forming ad-hoc multi-hop networks covering potentially vast geographic areas. This document describes a wireless PHY and related MAC extensions for the air interface to support home to grid and home to home aspects of the SUN. Individual links can be formed by peer devices with little dependency on network infrastructure. Each device will have modest data transfer requirements, and are optimized for low cost, simplicity, high availability, and efficient peer-to-peer ad-hoc (mesh) networking and extreme scalability over data rate.

1.2 Purpose

This document describes the Narrow Band PHY specifications optimized for frequency hopping, to support the SUN scope as described in the IEEE PAR (Project Authorization Request) approved by the IEEE Standards Association (see reference [1]). This proposal defines an amendment to IEEE 802.15.4 to address the Low Data Rate Wireless Smart Metering Utility Network requirements, defining an alternate PHY and associated MAC modifications needed to support its implementation.

1.3 Scope

The scope of this discussion includes primarily the NBFH PHY. MAC specifications are included in support of the proposed PHY.

Within this document, the term “PHY” means the NBFH PHY proposed.

2. References

1. https://mentor.ieee.org/802.15/file/08/15-08-0705-05-0nan-wnan-par.doc
2. http://standards.iso.org/ittf/PubliclyAvailableStandards/s020269_ISO_IEC_7498-1_1994(E).zip

3. Definitions

See next section

4. Acronyms, Abbreviations (and Definitions)

BWA = broadband wireless access

CRC = cyclic redundancy check

FEC = forward error correction

FCS = frame check sequence

FHSS = frequency hopping spread spectrum, a method of transmitting radio signals in which carriers tune to various channels following some known channel sequence.

FRC = free running clock

FSK = frequency shift keying, a frequency modulation scheme in which digital information is transmitted through discrete frequency changes of a carrier wave.

MFSK = minimum frequency shift keying, whereby the frequency distance between the highest and lowest discrete frequencies is equal to half the supported symbol rate.

GMSK = Gaussian minimum shift keying, a spectrally efficient form of MFSK where the sidelobes are attenuated using a Gaussian filter.

LDC = low duty cycle

LLC = logical link control

kHz = kilo hertz, that is one thousand hertz

kbps = kilo bits per second

ksps = kilo symbols per second

MAC = medium access control

MLME = MAC layer management entity

MPDU = MAC protocol data unit

NBFH = narrow band frequency hopping

NHL = next higher layer

OSI = open system interconnection

PAR = project authorization request

PHY = physical, generally refers to the physical layer of a communication device

PHR = PHY header

piconet = a collection of one or more communicating devices.

PPDU = PHY protocol data unit

PSDU = PHY service data unit

RSSI = received signal strength indicator

SAP = service access point

SHR = synchronization header

TPC = transmit power control

SOI = sphere of influence

SSCS = service specific convergence sub-layer

SUN = smart utility network

WLAN = wireless local area network

WPAN = wireless personal area network

5. General Description of SUN

5.1 Introduction

The SUN is a scalable network comprised of simple, low cost devices, with modest throughput requirements. The key objectives of this proposal are to extend 802.15.4 by including the SUN NBFH PHY and associated MAC additions, enhancing the capability of 802.15.4 to support scalability to many users, large packets and long ranges, high availability (robustness), highly reliable data delivery, and ease of commissioning. While the focus of this document is the PHY, in this section we present general characteristics of the SUN to provide context for the PHY requirements.

Some of the characteristics of the SUN as captured in the PAR include:

- Low data rate: over the air data rates of at least 40 kb/s and no more than 1 Mb/s
- Ubiquitous network with principally outdoor deployments
- Dynamic scaling to very large aggregate networks
- Support for PHY frame sizes of 1500 bytes or more

As reflected in the PAR, the vision is a network supporting a large number of nodes, each transmitting data at low rates, with packets of potentially significant size. A narrow band approach to the design of the PHY protocol offers the ability to support many users on different channels simultaneously, with good coexistence properties and minimal cross interference. Narrow band communication lends itself well to bandwidth scavenging and deployments in regions where bandwidth is scarce.

A large scale network implies a need for lost cost devices, to enable utility companies to deploy such networks in a pervasive, cost effective manner. The design choices in this proposal reflect the need for cost effective components. For example, we opt for simple FSK modulation with constant envelope, thus requiring only transmit chains with inexpensive power amplifiers, and receive chains that do not have linearity constraints.

Supporting large scale networks with minimal cost also implies the need for minimal infrastructure requirements and support for peer-to-peer networking where nodes can be used as intermediary points in connecting other nodes across large geographical distances. A narrow-band PHY protocol lends itself well to meshing due to its high degree of channel diversity, with collisions minimized despite the added channel traffic from intermediary meshing nodes.

Most instantiations of SUN will be ad-hoc, self forming mesh networks that connect utility network elements on a large scale. The Utility Network as a whole encompasses heterogeneous network technologies; the focus of this specification are the elements that fit between existing standards, which may be used in the utility backbone and the in-premises process, industrial and home area network. In this context, the SUN forms part of a heterogeneous network, filling the gap between the wide area BWA, industrial and consumer WPAN, and WLAN, as shown in the figure below.

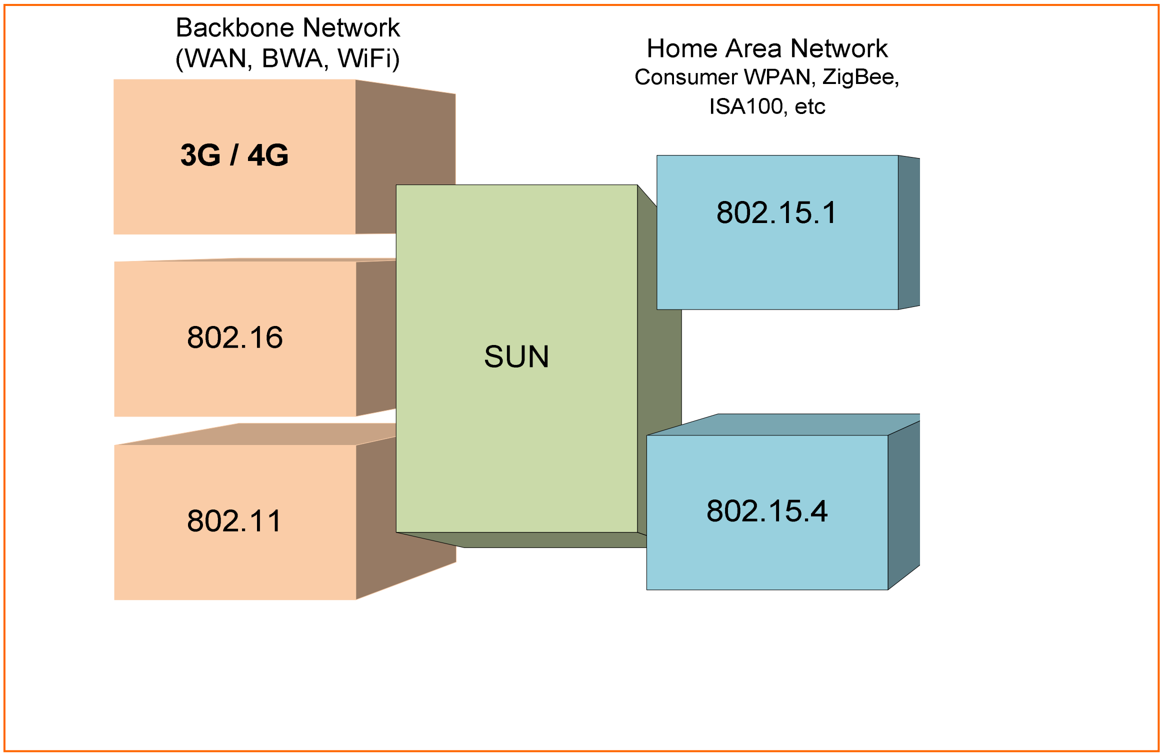


Figure 1: SUN Context

5.2 Components of the SUN

No changes proposed.

5.3 Network Topologies

The primary network operating topology required in a SUN is peer-to-peer where each node may communicate with every other node within its radio sphere of influence. This allows formation of ad hoc, self-organizing, and self-healing multi-hop mesh networks. The MAC and PHY layers provide the basic peer-to-peer communication capability. Services to support network forming and maintaining are provided by the MAC and higher layers. The ability to define logically separate networks within an overlapping SOI is also required; the PHY provides the capability to the MAC for simultaneously operating overlapping networks by several means of separation, such as use of different frequency hopping sequences. Other network topologies are also supported as described in the 802.15.4-2006 standard.

5.3.1 Peer-to-Peer Network

No changes proposed.

5.3.2 Star Network

No changes proposed.

5.4 Architecture

The SUN architecture is defined in terms of a number of layers. The layout of the layers is based on the OSI seven-layer model (see ISO/IEC 7498-1:1994, referenced in [2]). This document is concerned with the PHY and MAC layers.

A SUN device comprises a PHY, which contains the radio frequency (RF) transceiver along with its control mechanism, and a MAC sub-layer that provides access to the physical channel for all types of transfer. Figure 2 (repeated from 802.15.4-2006) shows the relationship of layers for an 802 PHY/MAC standard.

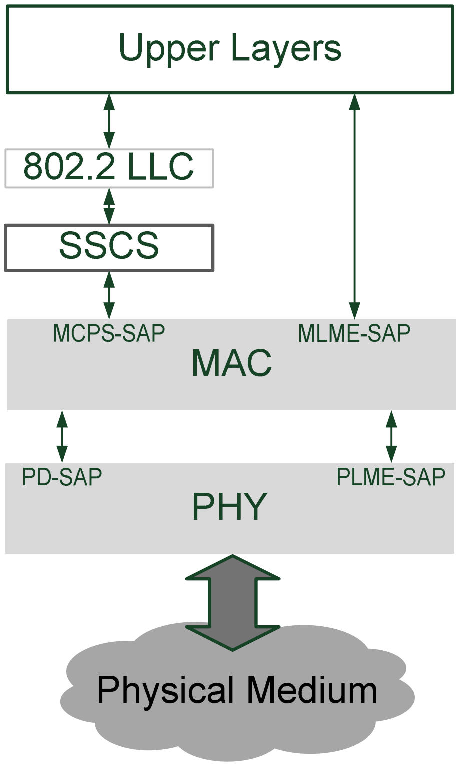


Figure 2: Device Architecture

The upper layers as shown in Figure 2 consist of a network layer, which provides network configuration, manipulation, and message routing, and an application layer, which provides the intended function of the device. This depiction is meant only to show the typical layer relationships: The definition of these upper layers is outside the scope of this standard. An IEEE 802.2 Type 1 LLC can access the MAC sub-layer through the service-specific convergence sub-layer, as defined in 802.15.4-2006 Annex A. The SUN architecture will typically be implemented as embedded devices without the support of an external device.

5.4.1 General Characteristics of the NBFH PHY Sub-layer

This section outlines the general capabilities of the NBFH PHY.

The PHY provides two services to the MAC layer as described in the existing 802.15.4 standard: the PHY data service and the PHY management service. The PHY data service enables the transmission and reception of PHY protocol data units between PHY entities across the physical radio channel. The PHY management service provides control of the physical channel, such as channel selection, channel condition measurement, and related functions.

The primary PHY layer considerations for SUN devices are ubiquity, robustness and scalability. It is critical to form a network with the ability to connect to/from every node in its sphere of influence. The PHY must provide the capabilities for adaptation to dynamic conditions in the environment, where nodes are deployed with nearly zero configuration effort at provisioning, and without the need to manually update nodes once deployed.

The combined requirements of low required data rate, high reliability/availability, and flexible adaptability are well addressed by a channel plan defined across multiple bands which provides a large number of narrow channels. The MAC controls frequency hopping, with flexible control options provided to the next higher layer. The PHY may operate in one or more of the following bands (but this list is not exhaustive or restrictive):

- 779-787 MHz (China)
- 840 to 956 MHz
    - 868–868.6 MHz (e.g. Europe, China, others)
    - 902–928 MHz (e.g., Americas, China, others)
    - 950-956 MHz (Japan)
    - 865.6-867.6, 840.5-844.5, others TBD
- 2400–2483.5 MHz (worldwide)

Other bands may be (or become) available in different regulatory domains. The intent of the standard PHY is to accommodate a flexible channel plan, and leave specific frequency specification to the implementer.

Determination of which bands may be used at a given time or in a given location are upper layer functions.

A summary of the proposed PHY operation and nominal parameters is captured in the following table for the bands 902-928 MHz and 2400-2483.5 MHz. Parameters for other bands may be included at a later point in time.

Parameter	NBFH-PHY
Operating band	sub- GHz (e.g. 902 MHz), 2.4GHz
Channel BW	< 250 kHz @ 20 dB down from peak
Channel spacing	300 kHz
Modulation	MFSK required, GMSK optional

FEC	None
Frequency Hopping	MAC controlled
PHY frame structure:	
■ MAX payload	2047 octets
■ SHR	At least 32 bits preamble + 16 bit SFD
■ CRC	CRC-32
Data Whitening	8-bit LFSR, variable seed
Data rate(s)	100 kbps
Symbol / chip rate	100 ksps
Transmit Power	As allowed by regulatory regimes
PSD	As allowed by regulatory regimes
TX Power Control	Yes
Chan availability, blacklisting	MAC or higher layer defined
Link Quality	RSSI
Reliability enhancing features/methods	Hopping, CRC-32, scrambling
Co-existence features	Channel diversity, LDC, TPC
Co-located network support	Channel diversity, LDC, TPC

The general characteristics of the PHY include:

- Narrow band channels with many channels per band
    - Ability to use maximum transmit power as may be allowed by regulations (for example under US FCC part 15.247, the criteria for 1W FHSS), and adjust transmit power to fit the local regulations
    - Robust performance in the presence of multiple interference sources
    - Maximum -20dB Bandwidth: 250kHz
    - Maximum non-overlapping channels that fit the band in use
- Optional operation in multiple bands
    - Ability to make use of small “slices” of under-used spectrum
- Support for efficient frequency hopping
    - Primarily band agnostic
    - Deterministic constraints on channel switch timing
    - Support for needed sync mechanisms
    - Support for channel “black-listing” and “white-listing”, whereby access to specific channels can be restricted or encouraged
- Support for large frame sizes
    - 2047 octet payload capable
    - 32-bit CRC PHY frame check sequence
    - Support for IP frames
- Robust, simple FSK modulation/demodulation
    - Ability to demodulate under conditions of simultaneous channel occupancy
    - Constant envelope modulation, independent of data patterns and pattern lengths

- Data “whitening” (scrambling)
    - Whitens payload data (PSDU/MPDU) to avoid long series of 1’s and 0’s.
    - 8-bit scrambler (255 bit sequence), taps at bits [8,4,3,2]
    - Scrambler re-seeded periodically for added reliability
- A nominal data rate of 100 kbps consistent with the PAR
- TPC for adapting to regulator domain and to support adaptation to observed link conditions
- Monotonic RSSI

Clause 6 specifies the PHY layer.

5.4.2 MAC Sub-layer (General Characteristics)

Consistent with the existing 802.15.4 standard, the MAC sublayer provides two services: the MAC data service and the MAC management service interfacing to the MLME service access point (MLME-SAP).The MAC data service enables the transmission and reception of MAC protocol data units between peer MAC entities across the PHY data service. The features of the MAC sub-layer required for support of the NBFH PHY include:

- Data exchange handshake and acknowledgement
- Link control and timing, including exchanging and maintaining relative timing information between peer nodes
- Medium access, including back-off algorithms
- Frequency hopping
- PHY configuration

The SUN is designed primarily for low-duty cycle applications. The MAC must be optimized for high data delivery reliability, low data throughput, effective support of IP traffic, and efficient support to upper layers for ad-hoc, multi-hop networking.

5.5 Functional Overview

A brief overview of the general functions of a SUN is given in the following sub-clauses, including information on the channel access, the data transfer model, the frame structures, and reliability provisions and considerations.

5.5.1 Superframe structure

No changes proposed.

5.5.2 Data Transfer Model

No changes proposed.

5.5.3 Peer-to-Peer Data Transfer Model

In a peer-to-peer SUN, every device may communicate with every other device in its radio sphere of influence. Peers within each other's SOI are referred to as directly connected or adjacent. In order to exchange data, the devices wishing to communicate will need frequency hopping sequence information at appropriate times, involving local synchronization of the affected nodes. No global synchronization is required for channel access and data transfer.

Frequency hopping is controlled by the MAC. To communicate with a peer MAC, the initiating MAC must have synchronization information for the destination node and calculate what channel the node is on within that node's channel sequence. The MAC provides:

- The process for acquiring synchronization information
- The targeting procedure for finding the destination node in its hopping sequence

5.5.4 Improving probability of delivery

Successful data delivery is improved by means of data scrambling, inclusion of a strong CRC, enablement of frequency hopping and robust data modulation techniques.

5.5.5 Power Consumption Considerations

Primary mechanisms for reducing power consumption in SUN applications are low device duty cycle, minimum overhead bits, collision avoidance via frequency hopping (thus reduced retry and receive time). Sleep schedules for powering-off receivers may be considered as well.

5.6 Concept of Primitives

A primitive can be one of four generic types:

- Request
- Indication
- Response
- Confirm

No changes proposed to the existing standard at this time.

6. PHY Specification

This section describes the PHY specification for a narrow-band, frequency hopping PHY. This section describes the functionality of the service interfaces. The NBFH PHY provides for effective use of license exempt frequency bands with a simple radio suitable for low cost implementations, high spectral efficiency, and good coexistence properties. Suitable separation mechanisms are included for overlapping piconets in the presence of overlapping SOI and given the need for SOI scaling.

6.1 General Requirements and Definitions

6.1.1 Operating frequency

The NBFH PHY is designed to operate over a variety of license exempt frequency bands. The narrow channel bandwidth enables use of many regionally available frequency bands, in small increments, making it possible to fit channels within small spaces in the spectrum. The following section defines channels plans for the common sub-GHz and the 2.4 GHz bands.

6.1.2 Channel assignments

The NBFH PHY divides each operating band into channels with an occupied bandwidth of less than 250 kHz, using 300 kHz channel spacing. The minimum 20dB bandwidth allowed is 200 kHz and the maximum 20dB bandwidth is 250 kHz.

The bands supported by this PHY include:

- Sub-GHz (902 MHz to 928 MHz)
- 2.4 GHz (2400 MHz to 2483.5 MHz)

[Note to the editor: Add appropriate entries in 802.15.4-2006 Table 1]

6.1.2.1 Channel numbering for the NBCH PHY

Band	# Chans	Width
902–928 MHz	85	300 kHz
2400–2483.5 MHz	261	300 kHz

In the 902–928 MHz band, the channel center frequency is computed using the following equation, where n is the channel number: 902.3 + (n*0.3) where n=0 to 84. The center frequencies for each channel in this band are included in the table below.

0: 902.30	10: 905.30	.	63: 921.20	76: 925.10
1: 902.60	11: 905.60	.	64: 921.50	77: 925.40
2: 902.90	12: 905.90	.	65: 921.80	78: 925.70
3: 903.20	13: 906.20		66: 922.10	79: 926.00
4: 903.50	14: 906.50		67: 922.40	80: 926.30
5: 903.80	15: 906.80		68: 922.70	81: 926.60
6: 904.10	16: 907.10		69: 923.00	82: 926.90
7: 904.40	17: 907.40		70: 923.30	83: 927.20
8: 904.70	18: 907.70		71: 923.60	84: 927.50

In the 2400–2483.5 MHz band, the channel center frequency is computed using the following equation, where n is the channel number: 2400.3 + (n*0.3) where n=0 to 260. The center frequencies for each channel in this band are included in the table below. A guard band of 5 MHz is allocated at the high end of this frequency band, to meet emission regulations associated with the restricted 2483.5 to 2500 MHz band.

0: 2400.30	.	.	.	258: 2477.7
1: 2400.60	.	.	.	259: 2478.0
2: 2400.90	.	.	.	260: 2478.3

6.1.2.2 Channel pages for the NBFH PHY

Compared to the existing 802.15.4-2006 standard, the number of channels per page needs to be increased to support the larger number of channels available with the narrow band PHY solution.

6.1.3 Minimum inter-frame spacing periods

The minimum inter-frame spacing is 0.

6.1.4 RF power measurements

Unless otherwise stated, all RF power measurements, on either transmit or receive chains, shall be made at the appropriate transceiver to antenna connector. The measurements shall be made with equipment that is either matched to the impedance of the antenna connector or corrected for any mismatch. For devices without an antenna connector, the measurements shall be interpreted as effective isotropic radiated power (EIRP) (i.e., a 0 dBi gain antenna), and any radiated measurements shall be corrected to compensate for the antenna gain in the implementation.

No changes from existing standard.

6.1.5 Transmit Power

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

6.1.6 Out-of-band spurious emissions

The out-of-band spurious emissions shall conform to local regulations. Refer to Annex F for additional information on regulatory limits on out-of-band emissions.

No changes from existing standard are proposed.

6.1.7 Receiver sensitivity definitions

The receiver sensitivity definitions used throughout this standard are defined in Table 1.

Term	Definition of term	Conditions
Packet error rate (PER)	Average fraction of transmitted packets that are not correctly received.	– Average measured over random PSDU data.
Receiver sensitivity	Threshold input signal power that yields a specified PER under AWGN conditions, no interferers.	– PSDU length = 1500 octets. – PER $\leq$ 1%. – Power measured at antenna terminals. – Interference not present.

Table 1 Receiver Sensitivity Definitions

6.2 PHY Service Specification

6.2.1 PHY Data Service

6.2.1.1 PD-DATA.request

6.2.1.1.1 Semantics of the service primitive

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

```
PD-DATA.request       (
                      psduLength,
                      psdu,
                      channel ID
                      )
```

Table 6 (Table 2: PD-DATA.request parameters) specifies the parameters for the PD-DATA.request primitive.

Name	Type	Valid range	Description
channelID	Unsigned integer	≤ *phyMaxChanSeqSize*	Channel ID (index) PSDU is to be transmitted on.

Table 2: PD-DATA.request parameters

6.2.1.1.2 Appropriate usage

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

6.2.1.1.3 Effect on receipt

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

If the PD-DATA.request primitive is received while the receiver is enabled (RX_ON state), the PHY entity will discard the PSDU and issue the PD-DATA.confirm primitive with a status of RX_ON. If the PD-DATA.request primitive is received while the transceiver is disabled (TRX_OFF state), the PHY entity will discard the PSDU and issue the PD-DATA.confirm primitive with a status of TRX_OFF. If the PD-DATA.request primitive is received while the transmitter is already busy transmitting (BUSY_TX state), the PHY entity will discard the PSDU and issue the PD-DATA.confirm primitive with a status of BUSY_TX.

6.2.1.2 PD-DATA.confirm

The PD-DATA.confirm primitive confirms the end of the transmission of an MPDU (i.e., PSDU) from a local PHY entity to a peer PHY entity. No changes.

6.2.1.2.1 Semantics of the service primitive

No changes.

6.2.1.2.2 When generated

No changes.

6.2.1.2.3 Appropriate usage

No changes.

6.2.1.3 PD-DATA.indication

6.2.1.3.1 Semantics of the service primitive

NBFH PHY additional parameters pertains to information regarding the received channel.

```
PD-DATA.indication    (
                      psduLength,
                      psdu,
                      ppduLinkQuality,
                      receiveChannel ID,
                      frameReceiptTime

                      )
```

Table below describes the PD-DATA.indication (added parameters for NBFH PHY):

Name	Type	Valid range	Description
ReceiveChannelID	Unsigned integer	≤ *phyMaxChanSeqSize*	Channel ID (index) PSDU is to be transmitted on.
frameReceiptTime	Unsigned integer	Implementation dependent	FRC value (see FRC sub-clause)

6.2.1.3.2 When generated

No changes.

6.2.1.3.3 Appropriate usage

No changes.

6.2.2 PHY Management Services

PLME-SAP primitive	**Request**	**Confirm**

There are no changes proposed at this time.

6.2.3 PHY enumerations description

Enumeration	**Value**	**Description**

There are no changes proposed at this time.

6.3 PPDU Format

The PHY frame structure is shown in Figure 3.

Octets: 7	2	1	2			variable	4
Bits: 56	16	8	4	1	11		32
Preamble	SFD	Scrambler Seed	RFU	EXT	Frame Length	(PSDU)	CRC-32
SHR		PHR				PHY Payload	FCS

Figure 3: Structure of NBFH PPDU

Synchronization Header (SHR): The SHR is not scrambled or encrypted (it is sent in the clear). It consists of two parts:

1. Preamble:
2. Start Frame Delimiter (SFD)

PHY Header (PHR): The PHY header is not scrambled or encrypted (it is sent in the clear). The PHR consists of the following:

1. Scrambler Seed
2. Frame Length
3. Reserved bits (RFU)
4. Extension bit

PHY Payload (PSDU) is sent scrambled. The PSDU may contain any valid MPDU.

Frame Check Sequence field is also scrambled and it is the standard IEEE CRC-32. This is computed and appended independent of the PHY payload content.

The bit order is to send the most significant bit and most significant byte first. The leftmost field as written on the page is transmitted and/or received first, consistent with the 802.15.4 convention.

6.3.1 Preamble Field

The preamble bits are sent prior to the 16-bit SFD. The purpose of the preamble is to provide for receiver centering, bit edge detection, and timing recovery. The preamble value is 7 octet sequence of an alternating one/zero bits (0xAA). Alternately the preamble may be set to any sequence by via the PHY PIB attribute *phyNBFHPreambleLength* and *phyNBFHPreambleValue* which set the number of preamble octets and the bit sequence to be used (the preamble is formed by repeating the 8-bit value *phyNBFHPreambleValue* by *phyNBFHPreambleLength* times). Refer to clause 6.4 for PIB descriptions.

[Note to technical editor: update Table 19 in 802.15.4-2006 with preamble lengths in symbols and durations in time]

6.3.2 SFD Field

A SFD shall be added to establish frame timing. The SFD indicates the end of the SHR and the start of the packet data, which begins with the PHY header. For the NBFH PHY the SFD is a 16-bit sequence with the value 0xF3A0 (*phyNBSFDValue*). Optionally, the implementation may provide for an alternate SFD value to be set by *phyNBSFDValue,* in which case the value selected must be different from the value of the preamble field. Refer to clause 6.4 for PIB descriptions.

Bit:0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1	1	1	1	0	0	1	1	1	0	1	0	0	0	0	0

Figure 4: Format of the SFD Field for NBFH PHY

[Note to technical editor: update Table 20 in 802.15.4-2006 with SFD lengths in symbols]

6.3.3 Scrambler Seed Field

This single octet value is used to seed the data scrambler. It allows the scrambler sequence to vary from packet to packet and across re-transmissions. Thus if the pathological case occurs where data “un-whitens” the packet scrambling with one scrambling seed, the retry can be received successfully with a different scrambling seed.

6.3.4 Frame Length Field

The 11 bits of the length field encode the size of the PSDU. Thus the maximum legal size of the PSDU (MPDU) is 2047 octets. The 32-bit CRC is not included in the PHY length specified in this field.

6.3.5 PHY Header Extension bit

This bit is reserved for future extension of the PHY header. For this version of the standard this bit shall be set to zero upon transmission. For future versions of the standard, a value of 1 in this field will be used to signal an extended version of the PHY header.

6.3.6 Reserved Bits

These are bits that are reserved for future use (RFU).

6.3.7 Frame Check Sequence Field

The Frame Check Sequence (FCS) is an IEEE CRC-32 (equivalent to ANSI X3.66-1979). On transmission, the CRC-32 is calculated over the PSDU (MPDU) prior to scrambling; on reception the FCS is calculated after de-scrambling. The FCS scope, referred to here as the calculation field, is the entire PHY payload (PSDU), and does not include the PHR.

The MSB of the FCS is the coefficient of the highest order term and the field is sent over the wireless medium commencing with the coefficient of the highest-order term.

The FCS is calculated using the following standard generator polynomial of degree 32:

G(x) = x32 + x26 + x23 + x22 + x16 + x12 + x11 + x10 + x8 + x7 + x5 + x4 + x2 + x + 1

The FCS is the one's complement of the modulo 2 sum of the remainders in "a" and "b" below:

a) The remainder resulting from ((xk*(x31+x30+...)) divided (modulo 2) by G(x). The value k is the number of bits in the calculation field.
b) The remainder resulting from the calculation field contents, treated as a polynomial, is multiplied by X32 and then divided by G(x).

At the transmitter, the initial remainder of the division shall be preset to all ones and is then modified via division of the calculation fields by the generator polynomial G(x). The ones complement of this remainder is the FCS field.

At the receiver, the initial remainder shall be preset to all ones. The serial incoming bits of the calculation fields and FCS, when divided by G(x) in the absence of transmission errors, results in a unique non-zero remainder value. The unique remainder value is the polynomial:

x31+x30+x26+x25+x24+x18+x15+x14+x12+x11+x10+x8+x6+x5+x4+x3+x+1

The above is the CRC-32 used in 802.11 and 802.15.3, among others.

6.3.8 PSDU Field

The PSDU field has a variable length and carries the data of the PHY packet.

6.4 PHY constants and PIB attributes

The constants for the NBFH PHY are shown below:

Constant	Description	Value
aMaxPHYPacketSize	The maximum PSDU size (in octets) the PHY shall be able to receive.	2047
aMaxNBFHPreambleLength	The maximum preamble size (in octets)	16

The PIB attributes for the NBFH PHY are shown in Table 3.

Attribute	**Identifier**	**Type**	**Range**	**Description**
phyNBFHPreambleLength		Int	4 - *aMaxNBFHPreambleLength*	Number of octets of preamble; Default = 7.
phyNBFHPreambleValue		Octet	0-0xff	Bit pattern for preamble. Default = 0xAA (alternating 1/0s)
phyNBSFDValue		16 Bits	0x0000-0xffff	NB PHY start of frame delimiter. Default value = 0xf3a0
phyNBFHTransmitPower		Int	*1 to phyNBFHNumPowerLevels*	The desired power level
phyNBFHNumPowerLevels		Int	1-255	The number of power levels supported. This is a read-only field, readable through a PLME-GET.request.
phyNBFHOutputPower		Array	*phyNBFHNumPowerLevels* of floating point numbers	For each power level, it stores the transmit power output value in units of dBm. This is a read-only field, readable through a PLME-GET.request.
phyMaxChanSeqSize†		Int		85 channels if *phyCurrentPage* = 8 (902 MHz band NBFH) and 282 channels if *phyCurrentPage* = 9 (2.4 GHz NBFH)
phyCurrentChannel	0x00	Integer	< *phyMaxChanSeqSize*	The RF channel to use for all following transmissions and receptions (see 6.1.2).
phyChannelsSupported†				
phyCurrentPage				Page 8 for band 902 MHz NBFH, Page 9 for band 2.4 GHz NBFH

Table 3 – NBFH PHY PIB Attributes

6.5 Narrow Band Frequency Hopping PHY Specification

This section is the detailed specifications for the Narrow Band Frequency Hopping PHY.

6.5.1 Data Rate(s)

The mandatory data rate is 100 kbps. Higher data rates may be implemented to achieve shorter transmit/receive times, lower duty cycles, and thus cause lower interference.

The 100 kbps data rate is achieved using FSK modulation, no FEC, a (nominally) 250 kHz 20dB bandwidth, and 300 kHz channel spacing. Higher data rates may be achieved using wider channels derived from concatenated basic channels, and/or higher order modulation techniques such as 4-FSK.

6.5.2 Data Transfer

Figure 5 shows the processing steps to create and transfer a PHY packet.

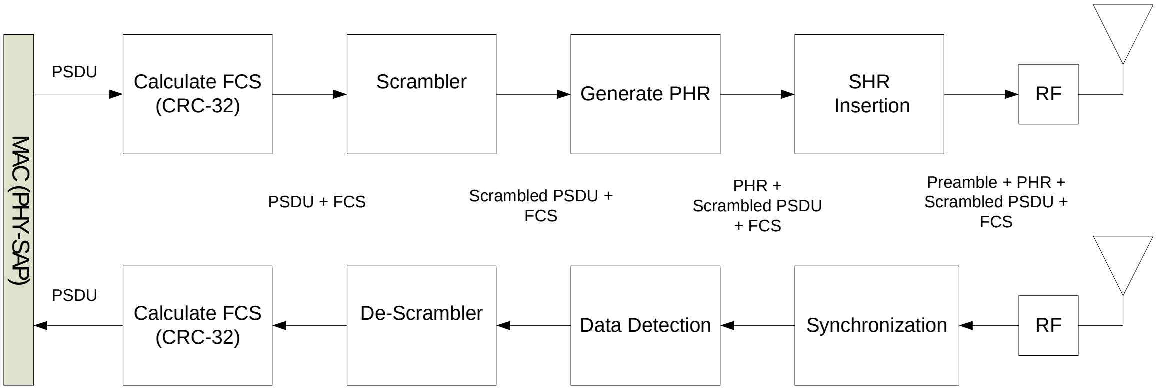


Figure 5: PHY Signal Flow

The PHY Frame format is shown in Figure 3. The steps to encode the PSDU (PHY Payload) into a PPDU for transmission are illustrated in Figure 6.

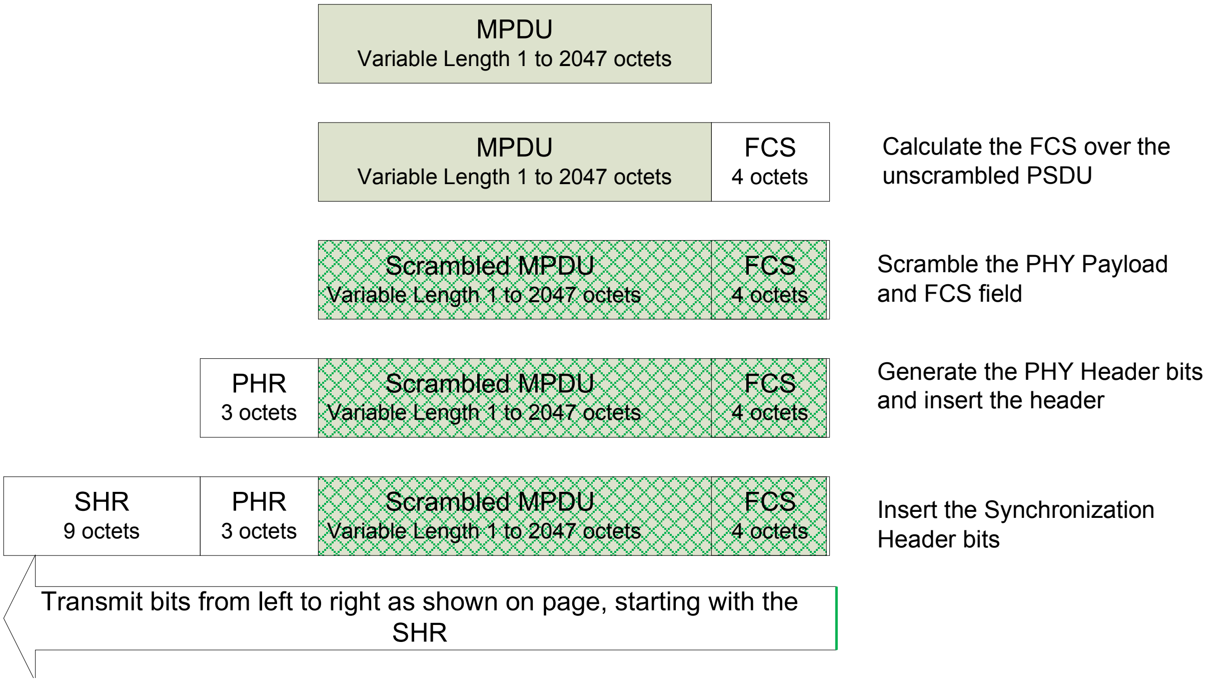


Figure 6: PPDU Encoding Process

6.5.3 Modulation and Coding

The NBFH PHY uses MFSK modulation (GMSK as an option) where the modulation index (the ratio of the difference in symbol modulation frequencies to the bit rate) is 0.5. Each data symbol encodes one information bit. At 100 ksps rates, the modulation deviation frequency (f_{dev}) is nominally 25 kHz, with up to ± 5 kHz of frequency offset.

6.5.3.1 Reference Modulator Diagram

The functional block diagram is shown in Figure 7. The frequency offset from center (deviation) is nominally 25 kHz at 100 ksps rates. The offset is toggled by the transmit data bit so that a positive offset is generated for a “1” and a negative offset is generated for a “0”.

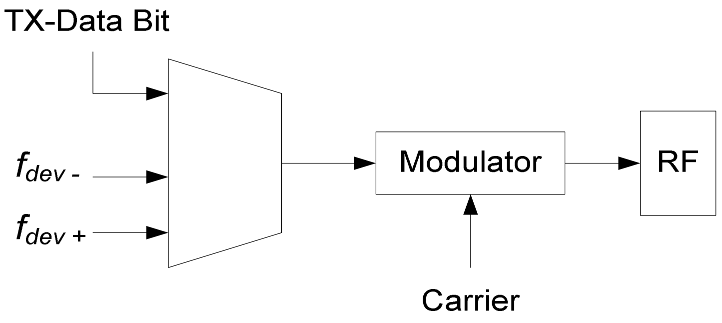


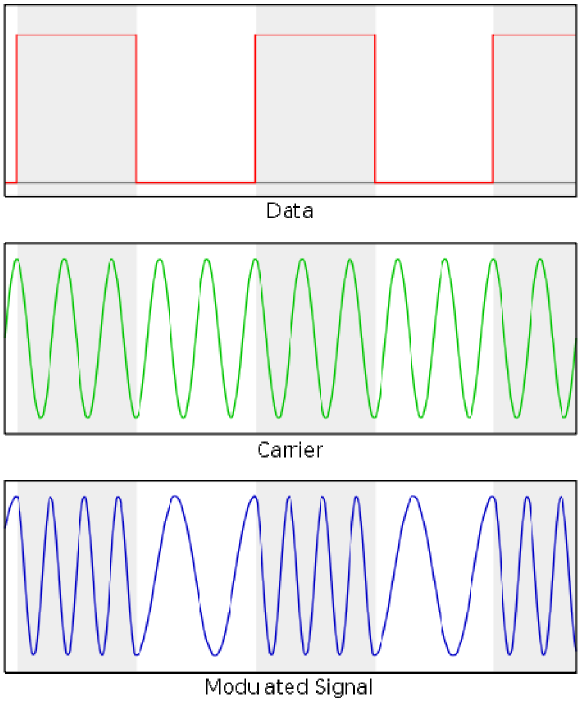
Figure 7: Reference Modulator Diagram

6.5.3.2 Bit to symbol mapping

Each FSK symbol represents one data bit as described above.

6.5.3.3 FSK Modulation

The modulated FSK signal is shown in the figure below:



The FSK modulation parameters are shown below.

Modulation index	0.5	
Frequency deviation	25kHz for bit 1 at 100 ksps	-25kHz for bit 0 at 100 ksps
Frequency deviation tolerance	± 5 kHz at 100 ksps	± 5 kHz at 100 ksps

6.5.4 Data Whitening

An 8-bit scrambler is applied to data bits to whiten the output. The scrambler is an additive, 8-stage (255 bit sequence) shift register generator with taps at bits [8,4,3,2] as shown in Figure 8.

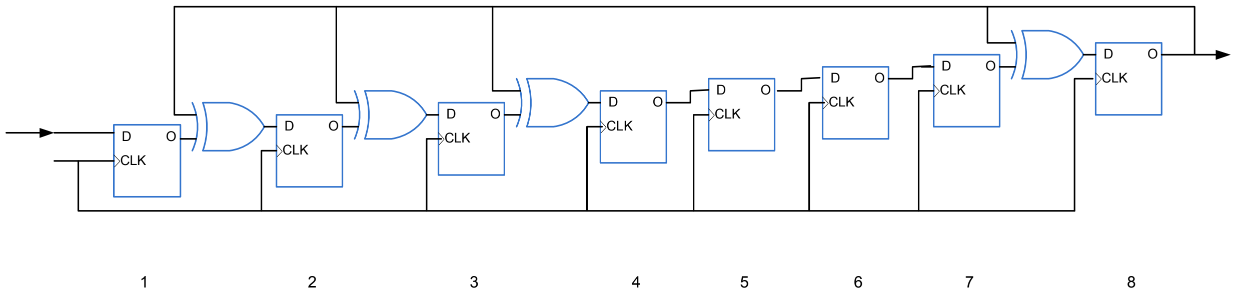


Figure 8: Scrambler Shift Register Representation

The transmitter scrambler seed is provided by the MAC for each PSDU. Note that if the scrambler is seeded with all zeros, it is effectively disabled, so this value should be avoided. On receive, the scrambler seed is set based on the Scrambler Seed value in the PHR.

The purpose of the scrambler is to whiten payload data to avoid long runs of 1's or 0's to maintain bit synchronization at the receiver. Nonetheless, for any scrambler seed, rare data sequences exist that can result in runs of 1's or 0's. Therefore, it becomes important to change the scrambling seed when retransmitting a given packet so that data that poses problems with one seed has the opportunity to get re-scrambled with a different seed.

6.5.5 Transmit Power Control

Transmit power control is used to enhance reliability, maximize spectral efficiency (reuse) by optimizing radio range (and thus SOI) to conditions, and enhance coexistence by reducing interference with other services. The transmit power is set via the *phyNBFHTransmitPower* parameter captured in the PIB table, that specifies the desired power level. The output power for that level is encoded in the *phyNBFHOutputPower* parameter in the same PIB table.

[Note to editor: need to update PIB table with this *phyNBFHTransmitPower* field].

6.5.6 NBFH other parameters

Parameters	**Value**	**Notes**
Minimum receiver sensitivity	-90 dBm	PER 10^{-2} for 1500 octet payload
Adjacent channel separation	300 kHz	
Alternate channel separation	600 kHz	
Adjacent channel rejection	10 dB	Measured at sensitivity + 3dB against a modulated signal with balanced 1's and 0's
Alternate channel rejection	30 dB	Measured at sensitivity + 3dB against a modulated signal with balanced 1's and 0's
Nominal modulation index	0.5	
Modulation index range	± 20%	To support ± 5 kHz
Nominal data rate	100 kb/s	
Data rate tolerance	± 1 kb/s	PN 9 encoded (run length <= 9)
Frequency tolerance/stability	± 10 ppm	

System time stability	+ 10 ppm	
TX amplifier rise time	< 100 us	
Channel switch time	< 500 us	

6.5.7 Free Running Clock (FRC)

It is required that a free running clock is available that can be accessed by both the PHY and MAC and used to time stamp packet receptions and schedule packet transmissions.

The PHY captures the time of PPDU arrival upon receipt. A snapshot of the FRC is taken at the receipt of the last bit of the scrambler seed. If available, the FRC value captured will be reported with the PSDU in the PD_DATA.indication.

The FRC may also be used by the MAC layer for scheduling packet transmissions to occur at a specific FRC value.

6.6 Blank Heading

6.7 Blank Heading

6.8 Blank Heading

6.9 General radio specifications

6.9.1 TX-to-RX turnaround time

The TX-to-RX turnaround time refers to the shortest time possible at the air interface from the trailing edge of the last symbol of a transmitted PPDU to the leading edge of the first symbol of the next received PPDU.

The TX-to-RX turnaround time shall be less than or equal to 1ms.

6.9.2 RX-to-TX turnaround time

The RX-to-TX turnaround time refers to the shortest time possible at the air interface from the trailing edge of the last symbol of the received PPDU to the leading edge of the first symbol of the next transmitted PPDU.

The RX-to-TX turnaround time shall be less than or equal to 1 ms and shall be greater than or equal to the TX-to-RX turnaround time.

6.9.3 Error-vector magnitude (EVM) definition

NA

6.9.4 Transmit center frequency tolerance

See table above.

6.9.5 Transmit power limits

6.9.6 Receiver maximum input level of desired signal

-20dBm

6.9.7 Receiver Energy Density

6.9.8 Link quality indicator (LQI)

The use of RSSI as part of LQI is proposed, as a monotonic variable with at least 3dB resolution and a total range of around 100 dB, covered with an 8-bit field.

6.9.9 Clear channel assessment (CCA)

A clear channel shall be indicated.

6.9.10 Channel to channel slew times (per band) (max)

The channel switch time shall not exceed 500 micro-seconds.

6.9.11 Transmit & power amplifier rise and fall times (max)

The power amplifier rise and fall times shall not exceed 100 micro-seconds.

7. MAC Sublayer Specification

The MAC sublayer handles all access to the physical radio channel and is responsible for the following:

- Providing a reliable link between peer MAC entities, achieved with packet acknowledgements and retransmissions
- Enforce regulatory constraints including channel occupancy limits and channel visit requirements
- Addressing
- Error detection
- Neighbor discovery
- Synchronizing (for frequency hopping)
- Channel selection (hopping control)
- Link quality assessment

7.1 MAC Service Specification

7.2 MAC Frame Formats

7.3 Constants and PIB Attributes

7.4 Functional Descriptions

7.4.1 Communications Link

7.4.2 Association and Disassociation

7.4.3 Synchronization

In order for a transmitter to send a packet to a node in the network, the transmitter needs to know the channel the receiver will be listening upon at any given time (see sub-clause 7.4.4 for more details). Knowledge of the channel can be accomplished by knowing the receiver frequency hopping sequence and knowledge of index into that sequence at the time of packet exchange.

Timing synchronization is important in NBFH systems as it is necessary for devices to communicate with each other. The NBFH system proposed herein uses “relative” time synchronization rather than global time synchronization. Relative time synchronization refers to devices communicating some form of timing information to their neighbors rather than all devices being synchronized to some global time source. The timing information communicated is always “synchronized” to a known point in the frame, namely the point of frame reception, as captured by the PHY and indicated to the MAC (the FRC value when a frame is received). Given the frame reception time and the timing information in the frame, upper layers can calculate the time, relative to itself (i.e the value of the FRC), that some event occurred (thus the term “relative timing” information).

The traversal of all the channels in a frequency hopping sequence is called an epoch. An important example of timing synchronization is the calculation of the epoch start time (see section 7.4.4.8). If device A transmits a frame with its epoch “tick” in it (synchronized to when the last bit of the channel ID is finished), device B can know the epoch start time of device A (relative to itself) by taking the receive time of the frame (as indicated by the PHY) and subtracting the epoch tick from it. Thus, device A now knows, relative to itself, when device B started its epoch.

7.4.4 Data Transfer

7.4.4.1 Transmission / Reception Overview

7.4.4.2 Priority

7.4.4.3 Handshake

7.4.4.4 Channel Access

7.4.4.5 Channel Hopping

The SUN MAC is intended to operate with the narrow-band PHY which provides a large number of channels for channel hopping. Each channel in a node’s hopping sequence is visited for an amount of time called the slot time. If no reception is heard during the slot time, the node changes to the next channel in its hopping sequence. If a reception is heard, channel hopping stops so that the reception can be processed.

When a frame is to be transmitted, channel hopping stops and the frame is sent on the specified channel if broadcast, or targeted to a node if sent to a unicast destination. Channel hopping resumes (from where it would have been had no transmit/reception occur) once the transaction ends.

Regulations in some regulatory domains specify that a nodes hopping sequence must visit all channels before revisiting a channel. The channel hopping procedure assures this by using a pseudo-random hopping sequence that repeats each epoch.

7.4.4.6 Hopping Sequence Exchange

In order for two devices to communicate, they must know the other's hopping sequence. The devices must exchange the sequence of channels that they will visit in the epoch. One simple encoding of this information is an ordered list of channel numbers and the band(s) to which each channel belongs.

7.4.4.7 Home Channel Receive Procedure

A receiving node follows the hopping sequence as described in this clause.

7.4.4.8 Targeting Procedure

In order to send a packet to a destination, a node must target the destination on its hopping sequence. The MAC must target a node such that the PHY header, up to and including the channel id, is received before the destination hops to its next channel. The targeting procedure requires the following information about the destination:

- slot duration
- the destination's hopping sequence
- epoch start time of the node
- clock accuracy.

Given these parameters, the channel on which the destination is receiving, or home slot and "slot tick" can be calculated for a given transmit time. The slot tick is the moment in time within the slot corresponding to the transmit time of the frame (i.e. the time at which the 1st bit of the preamble will appear). Note that the slot tick is unit-less and depends upon the instantiation and the accuracy with which timing synchronization information is conveyed.

The current home slot and slot tick of a device can be calculated as follows:

slot = ((transmit time – epoch start time) % epoch length) / slot time;

slot tick = (transmit time – epoch start time) % slot time;

For example, assume our timing resolution is in 1 millisecond units. The slot length is 20 milliseconds and the number of slots is 100. If the transmit time is 13122 milliseconds after the epoch start time, we would get a slot tick of 2 and a slot of 56. This means that the destination will be 2 milliseconds into the slot when the transmission begins and the channel will be the channel corresponding to slot 56 in its hopping sequence.

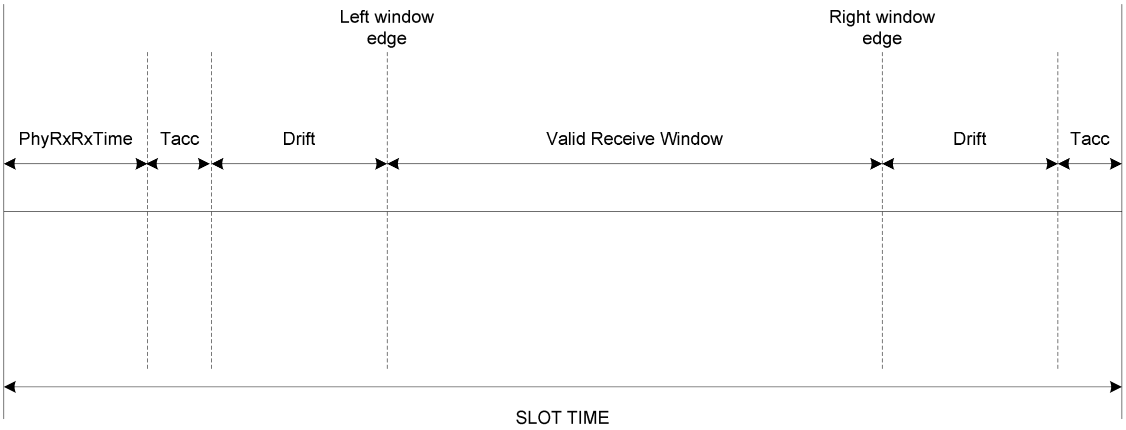


Figure 9: Slot Timing for Targeting

Figure 9 shows the slot timing when targeting and the Valid Receive Window (VRW). The VRW is defined as the amount of time within a slot that a targeting node can be sure the destination is receiving on the correct channel. A transmission must occur such that:

1) The 1st bit of the PHY preamble is sent at or after the left window edge, and
2) The PHY length field must start at or before the right window edge.

This means that the VRW must be equal to or greater than the duration of the PHY preamble, start word and channel ID.

The left edge of the VRW is calculated as follows. All devices in the network take a certain amount of time to change channels, defined by the PHY attribute *aPhyRxRxTime*. It is by definition that this time occurs at the beginning of a slot. The device must also account for all the various timing inaccuracies when determining the current slot tick, including epoch tick resolution and frame receive/begin timing resolution. This is shown as Tacc in the diagram and has a value equal to the MAC/DLL attribute *aMacTimingAccuracy*. Finally, the effect of crystal drift between the two devices must be taken into account.

If the slot tick at the time of the transmission is before the left window edge, transmission is delayed until the start of the left window. If the transmission starts after the left window of the slot, the time at which the channel id is finished is calculated. If that time is before the right window edge, the transmission begins immediately. If not, the transmission is timed to occur to start at the left window edge of the next slot.

7.4.4.9 Backoff Procedure

Exponential back-off will be used as in 802.15.4.

Annex A (normative) Service-specific convergence sublayer (SSCS)

This section will describe any additions which may be required for the SCCS.

Annex E (informative) Coexistence

Annex F (informative) Regulatory Limits

In the United States, the Federal Regulatory commission (FCC) imposes various regulations on radio frequency devices, captured in the Code for Federal Regulations, part 15, section 247, known as CFR 15.247. This section discusses a number of these rules.

Frequency hopping systems within the bands of 902–928 MHz, 2400–2483.5 MHz, and 5725–5850 MHz shall have hopping channel carrier frequencies separated by a minimum of 25 kHz or the 20 dB bandwidth of the hopping channel, whichever is greater.

For frequency hopping systems operating in the 902–928 MHz band: if the 20 dB bandwidth of the hopping channel is less than 250 kHz, the system shall use at least 50 hopping frequencies and the average time of occupancy on any frequency shall not be greater than 0.4 seconds within a 20 second period; if the 20 dB bandwidth of the hopping channel is 250 kHz or greater, the system shall use at least 25 hopping frequencies and the average time of occupancy on any frequency shall not be greater than 0.4 seconds within a 10 second period. The maximum allowed 20 dB bandwidth of the hopping channel is 500 kHz.

Frequency hopping systems in the 2400–2483.5 MHz band shall use at least 15 non-overlapping channels. The average time of occupancy on any channel shall not be greater than 0.4 seconds within a period of 0.4 seconds multiplied by the number of hopping channels employed. Frequency hopping systems which use fewer than 75 hopping frequencies may employ intelligent hopping techniques to avoid interference to other transmissions. Frequency hopping systems may avoid or suppress transmissions on a particular hopping frequency provided that a minimum of 15 non-overlapping channels are used.

The maximum peak output power of the intentional radiator shall not exceed the following:

- For frequency hopping systems in the 2400–2483.5 MHz band employing at least 75 hopping channels, and all frequency hopping systems in the 5725–5850 MHz band: 1 Watt. For all other frequency hopping systems in the 2400–2483.5 band: 0.125 Watt.
- For frequency hopping systems operating in the 902–928 MHz band: 1 watt for systems employing at least 50 hopping channels; and, 0.25 watts for systems employing less than 50 hopping channels, but at least 25 hopping channels.

[BLANK PAGE]