IEEE P802.15
Wireless Personal Area Networks

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Re:	Preliminary draft text
Abstract	Preliminary draft text resulting from decisions made starting from the January 2010 meeting until now.
Purpose	Preliminary draft text for discussion at the March 2010 meeting
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IEEE Draft Standard for
Information technology—
Telecommunications and information exchange between systems—
Local and metropolitan area networks—
Specific requirements—

Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)

Amendment 4: Physical Layer Specifications for Low Data Rate Wireless Smart Metering Utility Networks

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Abstract: This amendment to IEEE Std 802.15.4-2006 addresses principally outdoor low data rate, wireless, smart metering utility network requirements. It defines alternate PHYs and only those MAC modifications needed to support their implementation.
Keywords: ad hoc network, low data rate, low power, LR-WPAN, mobility, PAN, personal area network, radio frequency, RF, short range, smart metering utility networks, SUN, wireless, wireless personal area network, WPAN

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Introduction

This introduction is not part of IEEE P802.15.4g/d0.2, IEEE Draft Standard for Information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks—Specific requirements—Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)—Amendment 4: Physical Layer Specifications for Low Data Rate Wireless Smart Metering Utility Networks.

This amendment specifies alternate PHYs in addition to those of IEEE Std 802.15.4-2006, IEEE Std 802.15.4a-2007, IEEE Std 802.15.4c-2009, and IEEE Std 802.15.4d-2009. These alternate PHYs address principally outdoor low data rate, wireless, smart metering utility network requirements. This amendment defines the alternate PHYs and only those MAC modifications needed to support their implementation.

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Hiroshi Harada, *Task Group 4g Co-vice Chair*
Clinton C Powell, *Task Group 4g Co-vice Chair*
Monique B. Brown, *Task Group 4g Co-editor*
Kuor-Hsin Chang, *Task Group 4g Co-editor*
Stephen P. Pope, *Task Group 4g Secretary*

Major contributions were received from the following individuals: *<insert names here>*

The following members of the balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention. *<insert names here>*

When the IEEE-SA Standards Board approved this standard on *DD MM* 201x, it had the following membership: *<insert names here>*

,

Also included are the following nonvoting IEEE-SA Standards Board liaisons: *<insert names here>*

IEEE Standard for
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Specific requirements—

Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)

Amendment 4: Physical Layer Specifications for Low Data Rate Wireless Smart Metering Utility Networks

NOTE—The editing instructions contained in this amendment define how to merge the material contained therein into the existing base standard and its amendments to form the comprehensive standard.

The editing instructions are shown in ***bold italic***. Four editing instructions are used: change, delete, insert, and replace. ***Change*** is used to make corrections in existing text or tables. The editing instruction specifies the location of the change and describes what is being changed by using ~~strikethrough~~ (to remove old material) and underscore (to add new material). ***Delete*** removes existing material. ***Insert*** adds new material without disturbing the existing material. Deletions and insertions may require renumbering. If so, renumbering instructions are given in the editing instruction. ***Replace*** is used to make changes in figures or equations by removing the existing figure or equation and replacing it with a new one. Editing instructions, change markings, and this NOTE will not be carried over into future editions because the changes will be incorporated into the base standard.

4. Acronyms and abbreviations

Insert the following acronyms in alphabetical order:

AFA	adaptive frequency agility
CBD	channel band descriptor
CM	capabilities message
CP	cyclic prefix
CSM	common signaling mode
FCF	format change frame
FFT	Fast Fourier Transform
FSK	frequency shift keying
IFFT	inverse Fast Fourier Transform
LTF	long training field
MR-FSK	multi-rate and multi-regional frequency shift keying
MSK	minimum shift keying
NF	normal frame
NME	network management entity
OFDM	orthogonal frequency division multiplexing
RTJ	request to join
RTJR	request to join response
QAM	quadrature amplitude modulation
MR-O-QPSK	multi-rate and multi-regional offset quadrature phase-shift keying
SOI	sphere of influence
STF	short training field
SUN	smart utility network
TPC	transmit power control

5. General description

5.1 Introduction

Change the second paragraph of 5.1 as indicated:

Some of the characteristics of an LR-WPAN are as follows:

- Over-the-air data rates of 851 kb/s, 400 kb/s, 250 kb/s, 200 kb/s, 150 kb/s, 100 kb/s, 50kb/s, 40 kb/s, ~~and~~ 20 kb/s, 10 kb/s, and 5 kb/s
- Over-the-air data rates for MR-O-QPSK PHY of 31.25–500 kb/s or 15.625/62.5 kb/s (band dependent)
- Star or peer-to-peer operation
- Allocated 16-bit short or 64-bit extended addresses
- Optional allocation of guaranteed time slots (GTSs)
- Carrier sense multiple access with collision avoidance (CSMA-CA) or ALOHA [ultra-wide band (UWB)] channel access
- Fully acknowledged protocol for transfer reliability
- Low power consumption
- Energy detection (ED)
- Link quality indication (LQI)
- 16 channels in the 2450 MHz band, 30 channels in the 915 MHz band, 3 channels in the 868 MHz band, 14 overlapping chirp spread spectrum (CSS) channels in the 2450 MHz band, 16 channels in three UWB bands (500 MHz and 3.1 GHz to 10.6 GHz), 8 channels in the 780 MHz band, and 22 channels in 950 MHz band.

<editor's note: the final item in the above list gives the number of channels in each band. This is probably not a good idea for us. Suggestions are welcome.>

Change the last paragraph of 5.1 as indicated:

In addition, five ~~two~~ optional PHYs are specified:~~.~~ ~~A~~ a UWB PHY with optional precision range finding, ~~ranging is one option while~~ a 2450 MHz CSS PHY, and three PHYs targeting smart utility network (SUN) applications. ~~operating in the 2450 MHz band is the second.~~ The SUN PHYs are as follows: a multi-rate and multi-regional frequency shift keying (MR-FSK) PHY, a scalable orthogonal frequency division multiplexing (OFDM) PHY, and a multi-rate and multi-regional offset quadrature phase-shift keying (MR-OQPSK) PHY.

Insert the following new subclause after 5.1:

5.1a Introduction to P802.15.4g WPAN for smart utility networks (SUN)

P802.15.4g devices are designed to operate in very large-scale process control applications, such as SUNs. SUN devices often require the ability to use the maximum power available under applicable regulations, in order to provide long-range, point-to-point connections. Frequently, SUN installations are also required to cover geographically widespread communications to a large number of outdoor devices.

A true modern smart grid enables multiple applications to operate over a shared, interoperable network, similar in concept to the way the internet works today. To put this in perspective, the electrical network in the US alone is comprised of more than 300,000,000 metering endpoints, 14,000 transmission substations, 4,500 large substations for distribution, and 3,000 public and private owners.

5.2 Components of the IEEE 802.15.4 WPAN

Insert the following new subclause after 5.2:

5.2a Device class components of the P802.15.4g WPAN

In order to ensure that the wireless grid communications requirements are addressed in the most efficient manner possible, this draft standard defines three unique device classes to provide the capability of utilizing the most efficient methods of data transmission. The device class boundaries have been established based on the expected volumes of data to be transmitted during a typical 24-hour period. Each device class utilizes unique signaling attributes in order to maximize overall system performance.

Device Class A is defined as a class of devices forming a network capable of efficiently supporting data throughput for an average greater than 10,000,000 symbols per supported node during a single continuous 24-hour period.

Device Class B is defined as a class of devices forming a network capable of efficiently supporting data transfer for an average range of 10,000 symbols through 10,000,000 Symbols per supported node during a single continuous 24-hour period.

Device Class C is defined as a class of devices forming a network capable of efficiently supporting data transfer on an average of less than 10,000 symbols per supported node during in a single continuous 24-hour period.

5.3 Network topologies

5.4 Architecture

5.4.1 Physical layer (PHY)

Change the third paragraph in 5.4.1 as indicated:

The features of the PHY are activation and deactivation of the radio transceiver, ED, LQI, channel selection, clear channel assessment (CCA), and transmitting as well as receiving packets across the physical medium. The optional UWB PHY also has the optional feature of precision ranging. The radio operates at one or more of the following dedicated use or unlicensed bands:

Insert the following text to the end of the first dashed list in 5.4.1:

- 400–430 MHz (Japan)
- 450–470 MHz (United States)
- 470–510 MHz (People’s Republic of China)
- 863–870 MHz (Europe)
- 896–901 MHz (United States)
- 901–902 MHz (United States)
- 922 MHz (Korea)
- 928–960[1] MHz (United States)
- 1427–1518[1] MHz (United States, Canada)

---

[1] Non-contiguous.

Insert the following paragraph after the dashed list:

In addition to the unlicensed bands specified, the OFDM radio may also operate using TV white spaces.

5.4.1.1 Advantages of the UWB PHY for LR-WPAN

5.4.1.2 Advantages of the CSS (2450 MHz) PHY for LR-WPAN

5.4.1.3 UWB band coexistence

Insert the following subclause after 5.4.1.3:

5.4.1.3a Advantages of the OFDM PHY for LR-WPAN

The OFDM PHY uses a scalable FFT so that the OFDM Symbol Time and OFDM Frequency Subcarrier spacing can be maintained “constant” irrespective of the Bandwidth Option that is chosen. Bandwidth scaling from 1MHz down to less than 100KHz is achieved in this fashion by scaling the FFT options from 128 point FFT down to 8 point. Because of this, the OFDM Physical layer definition is “RF Band Agnostic” and enables low power operation. The high speed transmission rate means shorter Tx packets which results in lower duty cycle. OFDM is a spectrally efficient modulation with RF robustness and performance and is adaptable to multiple regulatory considerations.

5.5 Functional overview

5.5.1 Superframe structure

5.5.2 Data transfer model

5.5.3 Frame structure

5.5.3.1 Beacon frame

Replace Figure 10 with the new figure shown:

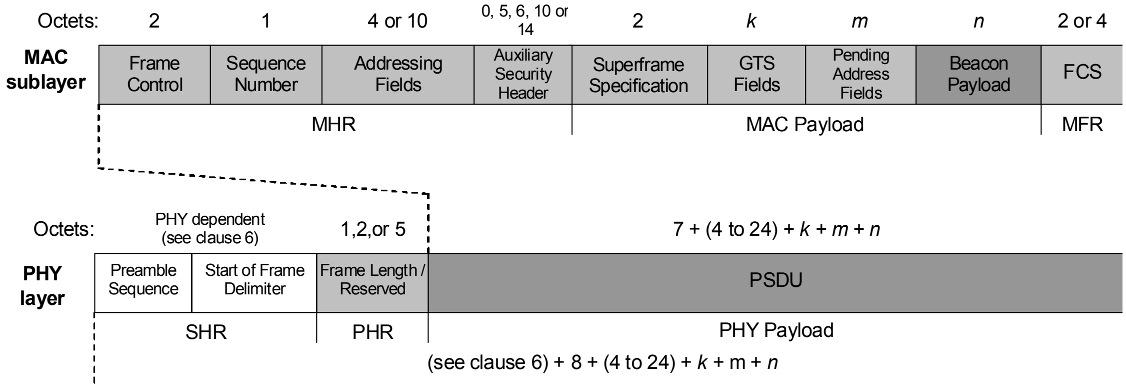


Figure 10—Schematic view of the beacon frame and the PHY packet

Insert the following figure (Figure 10a) after Figure 10:

Figure 10a shows the structure of the beacon frame and the OFDM PHY packet.

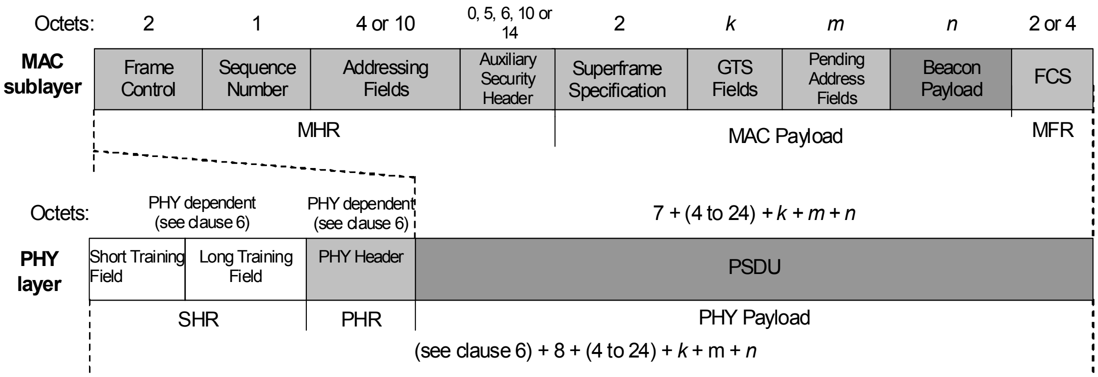


Figure 10a—Schematic view of the beacon frame and the OFDM PHY packet

5.5.3.2 Data frame

Replace Figure 11 with the new figure shown:

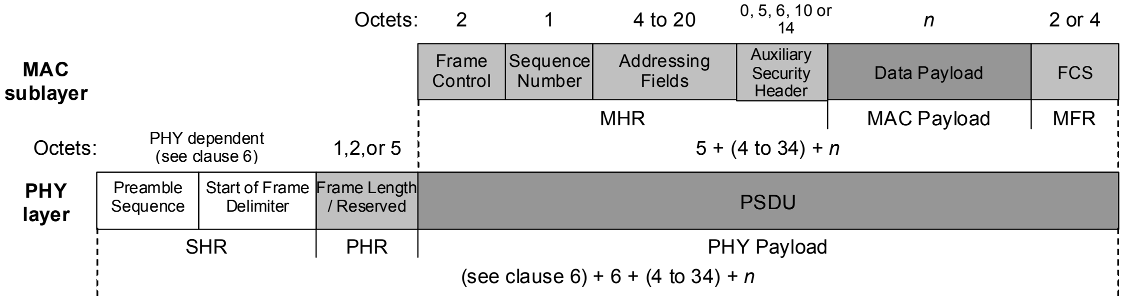


Figure 11—Schematic view of the data frame and the PHY packet

Insert the following figure (Figure 11a) after Figure 11:

Figure 11a shows the structure of the data frame and the OFDM PHY packet.

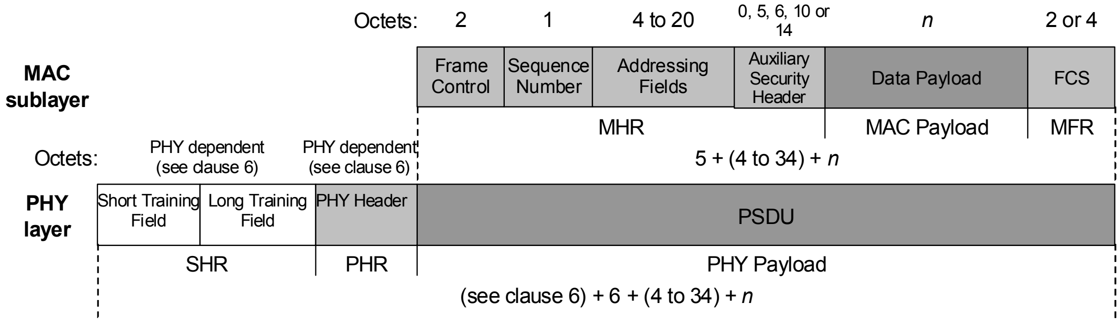


Figure 11a—Schematic view of the data frame and the OFDM PHY packet

5.5.3.3 Acknowledgment frame

Replace Figure 12 with the new figure shown:

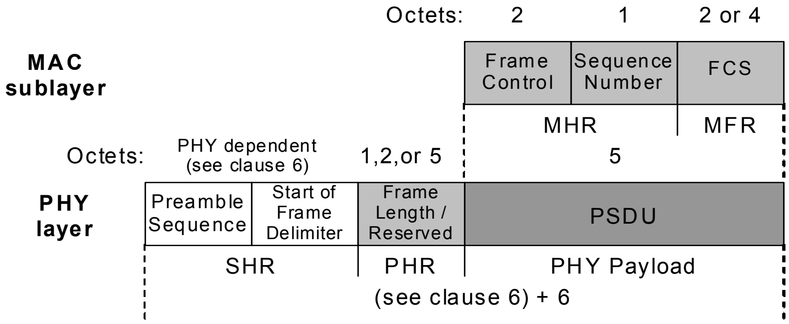


Figure 12—Schematic view of the acknowledgment frame and the PHY packet

Insert the following figure (Figure 12a) after Figure 12:

Figure 12a shows the structure of the acknowledgment frame and the OFDM PHY packet.

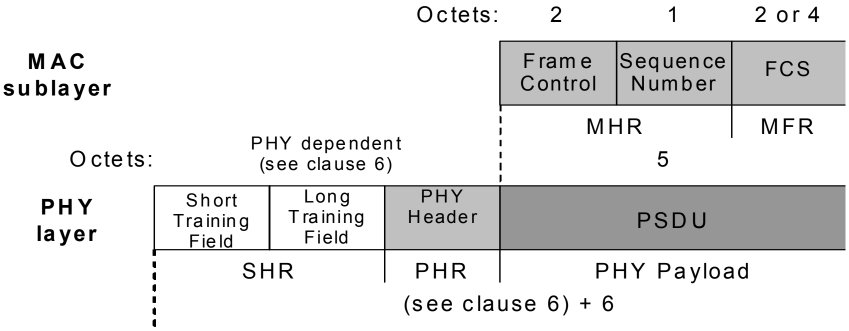


Figure 12a—Schematic view of the acknowledgment frame and the OFDM PHY packet

5.5.3.4 MAC command frame

Replace Figure 13 with the new figure shown:

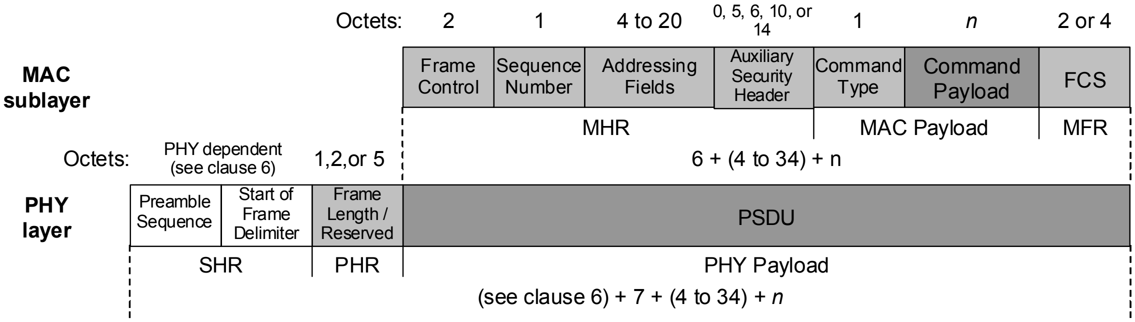


Figure 13—Schematic view of the MAC command frame and the PHY packet

Insert the following figure (Figure 13a) after Figure 13:

Figure 13a shows the structure of the MAC command frame and the OFDM PHY packet.

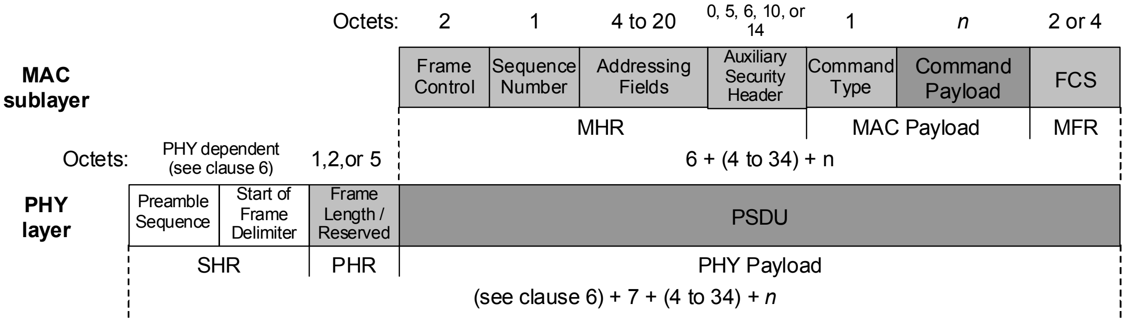


Figure 13a—Schematic view of the MAC command frame and the OFDM PHY packet

5.5.4 Improving probability of successful delivery

5.5.4.1 CSMA-CA mechanism

5.5.4.2 ALOHA mechanism for the UWB device

5.5.4.3 Frame acknowledgment

5.5.4.4 Data verification

5.5.4.5 Enhanced robustness features for the UWB PHY

Insert the following new subclause after 5.5.4.5:

5.5.4.5a Enhanced robustness features for the OFDM PHY

The OFDM PHY was specifically designed to provide enhanced robustness for LR-WPAN applications. This enhanced robustness is a result of several PHY features:

- The use of a cyclic prefix and frequency domain equalization using shifting pilot symbols provides very robust performance under harsh multipath conditions and Doppler spread (reflections caused by moving vehicles)
- A forward error correction (FEC) system provides flexible and robust performance under harsh multipath conditions.
- The use of frequency domain spreading provides robust performance even in low signal-to-noise ratio conditions.

6. PHY specification

6.1 General requirements and definitions

Insert the following items to the end of the first dashed list:

— Forward error correction (FEC) for the multi-rate and multi-regional frequency shift keying (MR-FSK) PHY (optional)

Insert the following paragraph at the end of 6.1 as indicated:

In addition to the PHYs supported in IEEE Std 802.15.4-2006, and IEEE Std 802.15.4a-2007, IEEE Std 802.15.4c-2009, and IEEE Std 802.15.4d-2009, the following PHYs targeting SUN applications have been added: multi-rate and multi-regional frequency shift keying (MR-FSK), orthogonal frequency division multiplexing (OFDM), and multi-rate and multi-regional offset quadrature phase-shift keying (MR-O-QPSK). Details on the MR-FSK, OFDM, and MR-O-QPSK PHYs are given in 6.12a, 6.12b, and 6.12c, respectively.

6.1.1 Operating frequency range

Change Table 1 (the entire table is not shown) as indicated:

Table 1—Frequency bands and data rates

PHY (MHz)	Frequency (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchip/s)	**Modulation**	**Bit rate (kb/s)**	**Symbol rate (ksymbols/s)**	**Symbols**
950[*][†]	950–956	—	GFSK	100	100	Binary
950[*][‡]	950–956	300	BPSK	20	20	Binary
400	TBD (1 MHz within 400–430 MHz)	—	GFSK	50	50	Binary
			GFSK	100[§]	100	
			GFSK	200	200	
			4-GFSK	400		4-ary
450	450–470	—	GFSK	5	5	Binary
				10	10	
				20	20	
470	470–510	—	GFSK	50	50	Binary
				100	100	
				200	200	
863	863–870	—	GFSK	50	50	Binary
				100	100	
				200	200	

Table 1—Frequency bands and data rates

869	869.4–869.65	—	GFSK	10	10	Binary
				20	20	
				40	40	
896	896–901	—	GFSK	10	10	Binary
				20	20	
				40	40	
901	901–902	—	GFSK	10	10	Binary
				20	20	
				40	40	
915	902–928	—	FSK	50	50	Binary
			FSK	150	150	
			GFSK	200	200	
928	928–960[**]	—	GFSK	10	10	Binary
				20	20	
				40	40	
950[††]	950–956	—	GFSK	50	50	Binary
			GFSK	100[§]	100	
			GFSK	200	200	
			4-GFSK	400		4-ary
1427	1427–1518[**]	—	GFSK	10	10	Binary
				20	20	
				40	40	
2450	2400–2483.5	—	FSK	50	50	Binary
			FSK	150	150	
			GFSK	200	200	
780	779–787	1000	O-QPSK	31.25–500 (see 6.12c)		
868	868–870	125	O-QPSK	15.625 and 62.5 (see 6.12c)		
915	902–928	1000	O-QPSK	31.25–500 (see 6.12c)		
2450	2400–2483.5	2000	O-QPSK	31.25–500 (see 6.12c)		
400	400–430	—	OFDM	See 6.12b		
470	470–510	—	OFDM	See 6.12b		
780	779–787	—	OFDM	See 6.12b		

Table 1—Frequency bands and data rates

863–870	863–870	—	OFDM	See 6.12b
915	902–928	—	OFDM	See 6.12b
922	917–923.5	—	OFDM	See 6.12b
950	950–960[‡‡]	—	OFDM	See 6.12b
2450	2400–2483.5	—	OFDM	See 6.12b
TV White Spaces		—	OFDM	See 6.12b

[*] ~~For the 950 MHz PHYs, at~~ At least one of the ~~two~~ 950 MHz PHYs shall be implemented when operating in Japan.
[†] As specified in 6.11.
[‡] As specified in 6.7.
[§] FEC scheme can be applied to reduce the data rate to 50 kbps, as described in 6.12a.1.4.
[**] Non-contiguous.
[††] As specified in 6.12a.
[‡‡] 956-960 band is future provisioning

Insert the following two tables and accompanying text after the second paragraph:

Table 1a shows the modulation and channel parameters for the mandatory and optional modes for the 450 MHz, 470 MHz, 863 MHz, 869 MHz, 896/901 MHz, 901/902 MHz, 915 MHz, 928/960 MHz, 1427/1518 MHz, and 2450 MHz bands. Table 1b shows the modulation and channel parameters for the mandatory and optional modes for the 400 MHz and 950 MHz Japanese bands.

Table 1a—MR-FSK modulation and channel parameters

Frequency band (MHz)	Parameter	Mandatory data rate	Optional data rate #1	Optional data rate #2
450–470 (FCC Part 22/90)	Data rate (kb/s)	5	10	20
	Modulation[*]	GFSK	GFSK	GFSK
	Modulation index	0.5	0.5	0.5
	First Channel Frequency	*BandEdge* + 31.25 kHz	*BandEdge* + 37.5 kHz	*BandEdge* + 50 kHz
	Channel spacing (kHz)	12.5	25	50
470–510 (China)	Data rate (kb/s)	50	100	200
	Modulation[*]	GFSK	GFSK	4-GFSK
	Modulation index	1.0	1.0	1/3
	First Channel Frequency	*BandEdge* + 300 kHz	*BandEdge* + 400 kHz	*BandEdge* + 400 kHz
	Channel spacing (kHz)[†]	200	400	400

Table 1a—MR-FSK modulation and channel parameters

Frequency band (MHz)	Parameter	Mandatory data rate	Optional data rate #1	Optional data rate #2
863–870 (Europe)	Data rate (kb/s)	50	100	200
	Modulation[*]	GFSK	GFSK	4-GFSK
	Modulation index	1.0	1.0	1/3
	First Channel Frequency	*BandEdge* + 300 kHz	*BandEdge* + 400 kHz	*BandEdge* + 400 kHz
	Channel spacing (kHz)	200	400	400
902–928 (ISM) 2400–2483.5 (Worldwide)	Data rate (kb/s)	50	150	200
	Modulation[*]	FSK	FSK	GFSK
	Modulation index	1.0	0.5	0.5
	First Channel Frequency	*BandEdge* + 300 kHz	*BandEdge* + 400 kHz	*BandEdge* + 400 kHz
	Channel spacing (kHz)	200	400	400
869 (EU G3) 896–901 (FCC Part 90) 901–902 (FCC Part 24) 928–960[‡] (FCC Part 22/24/90/101) 1427–1518[‡] (US FCC Part 90)/ (Canada SRSP 301.4)	Data rate (kb/s)	10	20	40
	Modulation[*]	GFSK	GFSK	GFSK
	Modulation index	0.5	0.5	0.5
	First Channel Frequency	*BandEdge* + 62.5 kHz	*BandEdge* + 75 kHz	*BandEdge* + 100 kHz
	Channel spacing (kHz)	25	50	100

[*] BT = 0.5.
[†] Channel spacing shows bundling of 200 kHz channels.
[‡] Non-contiguous.

Table 1b—MR-FSK modulation and channel parameters for Japanese bands

Frequency band (MHz)	Parameter	Mandatory data rate #1	Mandatory data rate #2	Optional data rate
400–430 (Japan) 950.1–955.7 (Japan)	Data rate (kb/s)	50	100	200/400
	Modulation[*]	GFSK	GFSK	GFSK/4-GFSK
	Modulation index	1.0	1.0	1.0/0.33
	Channel spacing (kHz)[†][‡]	200/400	400	600

[*] BT = 0.5.
[†] Channel separation of 200 kHz is used.
[‡] Channel spacing shows bundling of 200 kHz channels.

In addition to the modes in Table 1a and Table 1b, the MR-FSK PHY shall support a generic PHY mechanism to enable the derivation of a broader set of data rates and parameters; the specifications of the mandatory and optional modes just described are consistent with the generic PHY mechanism. Therefore, while a compliant device shall be capable of operating in the mandatory mode(s), the device may alternatively operate at a different data rate with associated parameter values, provided the alternative mode is compliant with the generic PHY mechanism. For an example of the use of the generic PHY mechanism, see Annex P.

The generic PHY mechanism defines the set of parameters necessary to describe a PHY mode. The set of PHY mode parameters is defined by the Generic PHY Descriptor (see 6.1.2.5a and Table 31a).

As described in 6.1.2.5a, Page 7 and Page 8 specify the operation of mandatory and optional modes, the PHY PIB attribute *phySUNPageEntriesSupported* lists the mode or mode supported by a specific device, and *phyCurrentSUNPageEntry* specifies the current PHY mode of operation.

The OFDM PHY covers each of the following frequency bands:

- International ISM 2.4 GHz
- United States 915 MHz
- Europe 863-870 MHz
- Japan 950-960 MHz
- China 783 MHz
- China 470-510 MHz
- Korea 922 MHz
- TV white spaces

6.1.2 Channel assignments

Insert the following new paragraph after the last paragraph of 6.1.2:

The introduction of the 400/470/863/915/950/2450 MHz FSK/GFSK/4-GFSK PHY specifications results in the total number of channel assignments exceeding the channel numbering capability of the 32 channel pages that were defined in IEEE 802.15.4-2006. To be consistent with existing channel page/channel number structures, channel page 7 and channel page 8 have been allocated for SUN applications with different definitions, as described in 6.1.2.5a.

6.1.2.1 Channel numbering

Change the first paragraph of 6.1.2.1 as indicated:

A total of 27 channels numbered 0 to 26 are available per channel page, except for the channel page 7 and 8, where the channel assignments are described in 6.1.2.5a.

6.1.2.2 Channel numbering for CSS PHY

6.1.2.3 Channel numbering for 779–787 MHz band

6.1.2.4 Channel numbering for 950 MHz PHYs

6.1.2.5 Channel numbering for UWB PHY

Insert the following new subclauses (6.1.2.5a–6.1.2.5a.4) after 6.1.2.5:

6.1.2.5a Channel numbering for SUN PHYs

Channel pages 0-6 allow up to 27 channels per page, where each bit in the channel page corresponds to a specific PHY mode channel. Each channel is for a specific PHY mode, where the frequency band, modulation scheme, and number of channels are defined and the channel bit in the channel page corresponds to a specific channel for the defined PHY mode.

To support the expanded number of channels required, the channel pages to support P802.15.4g-defined PHY modes will utilize a new definition. For P802.15.4g-defined PHY modes, the channel page is used to define the PHY mode, where the PHY mode definition is for a specific frequency band and modulation scheme. Channel page 7 will be used for standard defined PHY modes added with the P802.15.4g draft standard. The P802.15.4g draft standard also provides a mechanism where additional PHY modes can be defined with a Generic PHY mechanism. Channel page 8 will be used for Generic PHY defined PHY modes.

The page 7 and page 8 channel page structures are shown in Figure 22a. The contents of Channel Page 7 and Channel Page 8 are described in 6.1.2.5a.1 and 6.1.2.5a.2, respectively.

Bits: 31–27	**26–22**	**21–20**	**19–11**	**10**	**9–1**	**0**
Page 0	2450 MHz, O-QPSK, 16 channels			915 MHz, BPSK, 10 channels		*
:	:					
Page 6	Reserved	950 MHz, GFSK, 12 channels			950 MHz, BPSK, 11 channels	
Page 7	Frequency Band	Modulation Scheme	**Standard Defined PHY Modes** Bit map, where each bit corresponds to a particular PHY mode PHY modes are defined for each frequency band and modulation scheme			
Page 8	Reserved	Reserved	**Generic PHY Defined PHY Modes** Bit map, where a set bit indicates a Generic PHY mode supported by the device Each set bit position corresponds to an element in *phyGenericPHY-Descriptors*			
Pages 9–31	Reserved					

Figure 22a—Channel page structure for pages 7 and 8

6.1.2.5a.1 Channel page structure for standard defined PHY modes

Channel page 7 is allocated to the draft standard defined SUN PHY operating modes. As shown in Figure 22a, Page 7 consists of three fields to specify the SUN operating modes. The three fields are as follows:

- Frequency Band: 5 bits (bits 26–22) to define up to 32 possible frequency bands
- Modulation Scheme: 2 bits (bits 21–20) to define up to four modulation schemes
- PHY Mode: 20 bits (bits 19–0) to define up to 20 modes for each frequency band and modulation scheme

The integer values used to define the frequency bands are shown in Table 3a. The integer values used to define the modulation scheme are shown in Table 3b. The PHY mode definition is specific to the frequency band and modulation scheme. Each bit in the PHY mode field corresponds to a standard defined PHY mode for the particular frequency band and modulation scheme. Figure 22b through Figure 22i enumerate the standard defined PHY modes.

Table 3a—Frequency band definitions

Decimal	Binary (b_{26}, b_{25}, b_{24}, b_{23}, b_{22})	Description (MHz)
0	(0, 0, 0, 0, 0)	950 (Japan)
1	(0, 0, 0, 0, 1)	400–430 (Japan)
2	(0, 0, 0, 1, 0)	863–870
3	(0, 0, 0, 1, 1)	915
4	(0, 0, 1, 0, 0)	2400–2483.5
5	(0, 0, 1, 0, 1)	220–222 (US and Canada); 12.5kHz BW channels
6	(0, 0, 1, 1, 0)	450–470 (US FCC Part 90)
7	(0, 0, 1, 1, 1)	470–510 (China)
8	(0, 1, 0, 0, 0)	896–901 (US FCC Part 90)
9	(0, 1, 0, 0, 1)	901–902 (US FCC Part 24)
10	(0, 1, 0, 1, 0)	928–960 (US, non-contiguous)
11	(0, 1, 0, 1, 1)	1427–1452 (US and Canada, non-contiguous)
12	(0, 1, 1, 0, 0)	1492–1518 (US and Canada, non-contiguous)
13	(0, 1, 1, 0, 1)	1605–1625 (US, non-contiguous)
14	(0, 1, 1, 1, 0)	1800–1830 (US and Canada, non-contiguous)
15	(0, 1, 1, 1, 1)	779–787 (China)
16	(1, 0, 0, 0, 0)	922 (Korea)
17	(1, 0, 0, 0, 1)	TV white spaces
18–31	—	Reserved

Table 3b—Modulation scheme representation

Decimal	**Binary** (b_{21}, b_{20})	**Description**
0	(0, 0)	FSK/GFSK
1	(0, 1)	OFDM
2	(1, 0)	O-QPSK
3	(1, 1)	Reserved

Standard defined PHY modes are shown for the 950 MHz (Japan), 400–430 MHz (Japan), and 863–870 MHz bands in Figure 22b, Figure 22c, and Figure 22d, respectively.

Page bits: 31–27	**Freq Band 26–22**	**Mod Scheme 21–20**	**Standard Defined PHY Modes**	
			19–3	**2–0**
0 0 1 1 1	0 0 0 0 0	0 0	Reserved	1 1 1
Page 7	0 = 950	0 = (G)FSK	**Three standard defined PHY modes (bit positions 0–2)**	
Bit position 0 = 50 kbps, GFSK, mod index = 1.0, channel spacing = 200/400 kHz (mandatory mode)				
Bit position 1 = 100 kbps, GFSK, mod index = 1.0, channel spacing = 400 kHz				
Bit position 2 = 200/400 kbps, GFSK/4-GFSK, mod index = 1.0/0.33, channel spacing = 600 kHz				
Bit positions 3–19 = reserved				

Figure 22b—Frequency band 0, 950 MHz (Japan)

Page bits: 31–27	**Freq Band 26–22**	**Mod Scheme 21–20**	**Standard Defined PHY Modes**	
			19–3	**2–0**
0 0 1 1 1	0 0 0 0 1	0 0	Reserved	1 1 1
Page 7	1 = 400–430	0 = (G)FSK	**Three standard defined PHY modes (bit positions 0–2)**	
Bit position 0 = 50 kbps, GFSK, mod index = 1.0, channel spacing = 200/400 kHz (mandatory mode)				
Bit position 1 = 100 kbps, GFSK, mod index = 1.0, channel spacing = 400 kHz				
Bit position 2 = 200/400 kbps, GFSK/4-GFSK, mod index = 1.0/0.33, channel spacing = 600 kHz				
Bit positions 3–19 = reserved				

Figure 22c—Frequency band 1, 400–430 MHz (Japan)

Page bits: 31–27	Freq Band 26–22	Mod Scheme 21–20	Standard Defined PHY Modes	
			19–3	2–0
0 0 1 1 1	0 0 0 1 0	0 0	Reserved	1 1 1
Page 7	2 = 863–870	0=(G)FSK	**Three standard defined PHY modes (bit positions 0–2)**	
Bit position 0 = 50 kbps, GFSK, mod index = 1.0, channel spacing = 200 kHz (mandatory mode)				
Bit position 1 = 100 kbps, GFSK, mod index = 1.0, channel spacing = 400 kHz				
Bit position 2 = 200 kbps, 4-GFSK, mod index = 1/3, channel spacing = 400 kHz				
Bit positions 3–19 = reserved				

Figure 22d—Frequency band 2, 863–870 MHz

Standard defined PHY modes are shown for the 915 MHz band for FSK, OFDM, and O-QPSK modulations in Figure 22e, Figure 22f, and Figure 22g, respectively.

Page bits: 31–27	Freq Band 26–22	Mod Scheme 21–20	Standard Defined PHY Modes	
			19–3	2–0
0 0 1 1 1	0 0 0 1 1	0 0	Reserved	1 1 1
Page 7	3 = 915	0=(G)FSK	**Three standard defined PHY modes (bit positions 0–2)**	
Bit position 0 = 50 kbps, FSK, mod index = 1.0, channel spacing = 200 kHz (mandatory mode)				
Bit position 1 = 150 kbps, FSK, mod index = 0.5, channel spacing = 400 kHz				
Bit position 2 = 200 kbps, GFSK, mod index = 0.5, channel spacing = 400 kHz				
Bit positions 3–19 = reserved				

Figure 22e—Frequency band 3, 915 MHz with FSK modulation

Page bits: 31–27	**Freq Band 26–22**	**Mod Scheme 21–20**	**Standard Defined PHY Modes**	
			19–3	**2–0**
0 0 1 1 1	0 0 0 1 1	0 1	Reserved	1 1 1
Page 7	3 = 915	1 = OFDM	**Three standard defined PHY modes (bit positions 0–2)**	
Bit position 0 =				
Bit position 1 =				
Bit position 2 =				
Bit positions 3–19 = reserved				

Figure 22f—Frequency band 3, 915 MHz with OFDM modulation

Page bits: 31–27	**Freq Band 26–22**	**Mod Scheme 21–20**	**Standard Defined PHY Modes**	
			19–3	**2–0**
0 0 1 1 1	0 0 0 1 1	1 0	Reserved	1 1 1
Page 7	3 = 915	2 = O-QPSK	**Three standard defined PHY modes (bit positions 0–2)**	
Bit position 0 = chip rate = 1000 kchip/s, 16,1 spreading, data rate = 31.25 kbps				
Bit position 1 = chip rate = 1000 kchip/s, 16,4 spreading, data rate = 125 kbps				
Bit position 2 = chip rate = 1000 kchip/s, no spreading, data rate = 250 kbps				
Bit position 3 = chip rate = 1000 kchip/s, no spreading, data rate = 500 kbps				
Bit positions 4–19 = reserved				

Figure 22g—Frequency band 3, 915 MHz with O-QPSK modulation

Standard defined PHY modes are shown for the 2400–2483.5 MHz band inFigure 22h.

Standard defined PHY modes for the 220–222 MHz (US and Canada) and 450–470 MHz (US FCC Part 90) bands are TBD.

Standard defined PHY modes are shown for the 470–510 MHz (China) band inFigure 22i.

Standard defined PHY modes for the 896–901 MHz (US FCC Part 90), 901–902 MHz (US FCC Part 24), 928–960 MHz (US), 1427–1452 MHz (US and Canada), 1492–1518 MHz (US and Canada), 1605–1625 MHz (US), 1800–1830 MHz (US and Canada), 779–787 MHz (China), 922 MHz (Korea), and TV white space bands are TBD.

Page bits: 31–27	Freq Band 26–22	Mod Scheme 21–20	Standard Defined PHY Modes	
			19–3	**2–0**
0 0 1 1 1	0 0 1 0 0	0 0	Reserved	1 1 1
Page 7	4 = 2400	0 = (G)FSK	**Three standard defined PHY modes (bit positions 0–2)**	
Bit position 0 = 50 kbps, FSK, mod index = 1.0, channel spacing = 200 kHz (mandatory mode)				
Bit position 1 = 150 kbps, FSK, mod index = 0.5, channel spacing = 400 kHz				
Bit position 2 = 200 kbps, GFSK, mod index = 0.5, channel spacing = 400 kHz				
Bit positions 3–19 = reserved				

Figure 22h—Frequency band 4, 2400–2483.5 MHz

Page bits: 31–27	Freq Band 26–22	Mod Scheme 21–20	Standard Defined PHY Modes	
			19–3	**2–0**
0 0 1 1 1	0 0 1 1 1	0 0	Reserved	1 1 1
Page 7	7 = 470–510	0 = (G)FSK	**Three standard defined PHY modes (bit positions 0–2)**	
Bit position 0 = 50 kbps, GFSK, mod index = 1.0, channel spacing = 200 kHz (mandatory mode)				
Bit position 1 = 100 kbps, GFSK, mod index = 1.0, channel spacing = 400 kHz				
Bit position 2 = 200 kbps, 4-GFSK, mod index = 1/3, channel spacing = 400 kHz				
Bit positions 3–19 = reserved				

Figure 22i—Frequency band 7, 470–510 MHz (China)

6.1.2.5a.2 Channel page structure for Generic PHY modes

Channel Page 8 is used to list Generic PHY operating modes. As shown in Figure 22a, the channel page 8 structure uses the least significant 20 bits to represent the available Generic PHY descriptors. Each bit corresponds to the Generic PHY Id (0-19), and the Id is the index (0-19) in the *phyGenericPHYDescriptors* array. In Channel Page 8, the bit fields used to represent frequency band and modulation scheme are reserved and the frequency band and modulation scheme are defined by the Generic PHY descriptor.

A generic PHY descriptor consists of fields to define a specific frequency band (Channel Descriptor), a particular modulation scheme, and parametric descriptors that are specific to the modulation scheme. A generic

PHY descriptor is shown in Figure 22j. The *phyGenericPHYDescriptors* array consists of up to 20 generic PHY descriptors. For an example of the use of the generic PHY mechanism, refer to Annex M.

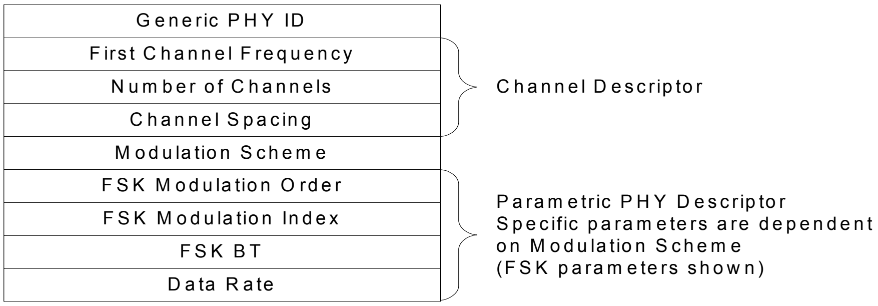


Figure 22j—Generic PHY descriptor

Generic PHY Channel Descriptor

The channels available in the Generic PHY Descriptor mode are defined by the following fields:

- First channel frequency is the center frequency of the first channel
- Number of channels is the number of contiguous channels starting at the first channel frequency
- Channel spacing is the spacing between adjacent channels

Generic PHY Modulation Scheme and Modulation Scheme Specific Parameters

The generic PHY mode is described by a modulation scheme, and then by parameters or descriptors that are specific to the modulation scheme. FSK is the only modulation scheme with defined parameters. A generic PHY FSK modulation scheme is defined by the following parameters:

- FSK Modulation Order is enumerated as 2-level or 4-level FSK
- FSK Modulation Index
- FSK BT defines if the mode is FSK or GFSK by specifying a value for BT

Generic PHY Data Rate

Regardless of modulation scheme, the data rate defines the raw over-the-air bit rate for the generic PHY mode.

6.1.2.5a.3 Channel numbering for MRFSK PHY

The channel center frequency *ChanCenterFreq* shall be derived using Equation (1), where *BandEdge* is the start of the frequency band in MHz, *NumChan* is the channel number, *ChanSpacing* is the channel separation in MHz, and *GuardBand* is the guard band of each frequency band that is equal to one half of the highest *ChanSpacing* of that particular frequency band. In Japan, the channel separation for the modes defined in Table 1b is 200 kHz. In all other bands, the channel separation is 200 kHz for the mandatory mode and 400 kHz for the optional modes (see Table 1a). The generic PHY mechanism allows other channel separations to be used in all bands.

$$ChanCenterFreq = BandEdge + GuardBand + (NumChan - 1) \times ChanSpacing \qquad (1)$$

Exceptions may apply to the upper part of the European 868 MHz band, where channel carrier assignment may be individually tailored to suit regulatory requirements.

6.1.2.5a.4 Channel numbering for MR-O-QPSK PHY

Channel numbering for 779–787 MHz frequency band

For channel page 0, 4 channels numbered 0 to 3 are available across the 779-787 MHz band. The center frequency of these channels is defined as follows:

$$F_c = 780 + 2k \text{ in megahertz, for } k = 0, \ldots, 3 \tag{2}$$

where k is the channel number.

Channel numbering for 868–870 MHz frequency band

For channel page 1, 3 channels numbered 0 to 2 are available across the 868–870 MHz band. The center frequency of these channels is shown in Table 3c.

Table 3c—Center frequencies for the MR-O-QPSK PHY of the 868–870 MHz band

Channel number	Center frequency (MHz)
0	868.300
1	868.950
2	869.525

Channel numbering for 902–928 MHz frequency band

For channel page 2, 10 channels numbered 0 to 9 are available across the 902–928 MHz band. The center frequency of these channels is defined as follows:

$$F_c = 906 + 2k \text{ in megahertz, for } k = 0, \ldots, 9 \tag{3}$$

where k is the channel number.

Channel numbering for 2400–2483.5 MHz frequency band

For channel page 3, 16 channels numbered 0 to 15 are available across the 2400–2483.5 MHz band. The center frequency of these channels is defined as follows:

$$F_c = 2405 + 5k \text{ in megahertz, for } k = 0, \ldots, 15 \tag{4}$$

where k is the channel number.

6.1.2.6 Channel pages

Change Table 4 (the entire table is not shown) as indicated:

Table 4—Channel page and channel number

Channel page (decimal)	Channel page (binary) (b_{31}, b_{30}, b_{29}, b_{28}, b_{27})	Channel number(s) (decimal)	Channel number description
7	0 0 1 1 1	—	Enumerates the standard defined PHY modes added with the P802.15.4g draft standard (see 6.1.2.5a.1). The channel page is used to define the frequency band, modulation scheme, and PHY mode. The channels are defined by *phySUNChannelsSupported*.
8	0 1 0 0 0	—	Enumerates the SUN PHY modes defined using the Generic PHY mechanism (see 6.1.2.5a.2). The channel page is used to define the frequency band, modulation scheme, and PHY mode. The channels are defined by *phySUNChannelsSupported*.
9–31	0 1 0 0 1–1 1 1 1 1	Reserved	Reserved

6.1.3 Minimum long interframe spacing (LIFS) and short interframe spacing (SIFS) periods

Insert the following new row at the end of Table 5:

Table 5—Minimum LIFS and SIFS period

PHY	*macMinLIFSPeriod*	*macMinSIFSPeriod*	Units
MR-FSK	40	12	Symbols

6.1.4 RF power measurement

6.1.5 Transmit power

TBD

6.1.6 Out-of-band spurious emission

6.1.7 Receiver sensitivity definitions

Change the first paragraph of 6.1.7 as indicated:

The receiver sensitivity definitions used throughout this draft standard for every PHY except the OFDM PHY are defined in Table 6. The receiver sensitivity definition for the OFDM PHY is defined in 6.12b.4.2.

Insert text into Table 6 (the entire table is not shown) as indicated:

Table 6—Receiver sensitivity definitions

Term	Definition of term	Conditions
Receiver sensitivity	Threshold input signal power that yields a specified PER.	– PSDU length = 250 octets for MR-FSK PHY, 20 octets for all other PHYs. – PER < 1%. – Power measured at antenna terminals. – Interference not present. – For the MR-FSK PHY, FEC disabled.

6.2 PHY service specifications

6.2.1 PHY data service

6.2.1.1 PD-DATA.request

6.2.1.1.1 Semantics of the service primitive

Insert the following new parameters at the end of the list in 6.2.1.1.1 (before the closing parenthesis):

TxChannel,
PHRCoding,
PayloadCoding,
FCSLength,
ModeSwitching

Insert the following new rows at the end of Table 8:

6.2.1.1.2 Appropriate usage

6.2.1.1.3 Effect on receipt

Change the first paragraph of 6.2.1.1.3 as indicated:

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 specified by the TxChannel parameter. Provided the transmitter is enabled (TX_ON state) and the transmit channel specified by the TxChannel parameter is supported, 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.

Insert the following three new paragraphs after the third paragraph of 6.2.1.1.3:

Table 8—PD-DATA.request parameters

Name	Type	Valid range	Description
TxChannel	Integer	See 6.1.2	The channel on which to send the PPDU.
PHRCoding	Boolean	TRUE or FALSE	A value of FALSE indicates that PHR coding is either turned off or not supported, and a value of TRUE indicates that PHR coding is turned on.
PayloadCoding	Boolean	TRUE or FALSE	A value of FALSE indicates that PHY payload coding is either turned off or not supported, and a value of TRUE indicates that PHY payload coding is turned on.
FCSLength	Enumeration	SHORT_FCS, LONG_FCS	The length of the FCS contained in the PSDU to be transmitted. A value of SHORT_FCS indicates a 16-bit FCS, and a value of LONG_FCS indicates a 32-bit FCS.
ModeSwitching	Boolean	TRUE or FALSE	A value of TRUE indicates that mode switching will occur with the next PPDU. A value of FALSE indicates that mode switching will not occur with the next PPDU (i.e., the current mode will be used for the following PPDU).

If the TxChannel parameter of the PD-DATA.request primitive specifies a channel that is not supported by the current PHY configuration, the PHY entity will issue the PD-DATA.confirm primitive with a status of UNSUPPORTED_TX_CHANNEL.

If the PHRCoding parameter of the PD-DATA.request primitive specifies that FEC coding is to be applied to the PHR but the feature is either disabled or not supported, the PHY entity will issue the PD-DATA.confirm primitive with a status of UNSUPPORTED_PHR_FEC. If the PayloadCoding parameter of the PD-DATA.request primitive specifies that FEC coding is to be applied to the PHY payload but the feature is either disabled or not supported, the PHY entity will issue the PD-DATA.confirm primitive with a status of UNSUPPORTED_PAYLOAD_FEC.

If the ModeSwitching parameter of the PD-DATA.request primitive specifies that mode switching is to occur before transmitting the next PPDU but the feature is not supported, the PHY entity will issue the PD-DATA.confirm primitive with a status of UNSUPPORTED_MODE_SWITCHING.

6.2.1.2 PD-DATA.confirm

6.2.1.2.1 Semantics of the service primitive

Change Table 9 (the entire table is not shown) as indicated:

6.2.1.2.2 When generated

Change the paragraph as indicated:

The PD-DATA.confirm primitive is generated by the PHY entity and issued to its MAC sublayer entity in response to a PD-DATA.request primitive. The PD-DATA.confirm primitive will return a status of either SUCCESS, indicating that the request to transmit was successful, or an error code of RX_ON, TRX_OFF, ~~or~~ BUSY_TX, UNSUPPORTED_CHANNEL, UNSUPPORTED_PHR_FEC,

Table 9—PD-DATA.confirm parameters

Name	Type	Valid range	Description
status	Enumeration	SUCCESS, RX_ON, TRX_OFF, BUSY_TX, ~~or~~UNSUPPORTED_PRF, UNSUPPORTED_RANGING, UNSUPPORTED_TX_CHANNEL, UNSUPPORTED_PHR_FEC, UNSUPPORTED_PAYLOAD_FEC, or UNSUPPORTED_MODE_SWITCHING	The result of the request to transmit a packet. A value of UNSUPPORTED_PRF indicates that the PHY is not capable of transmitting at the requested PRF. A value of UNSUPPORTED_RANGING is returned if the PHY does not implement a ranging counter.

UNSUPPORTED_PAYLOAD_FEC, or UNSUPPORTED_MODE_SWITCHING. The reasons for these status values are fully described in 6.2.1.1.3.

6.2.1.2.3 Appropriate usage

6.2.1.3 PD-DATA.indication

6.2.1.3.1 Semantics of the service primitive

Insert the following new parameter at the end of the list in 6.2.1.3.1 (before the closing parenthesis):

RxChannel,
FCSLength

Insert the following new row at the end of Table 10:

Table 10—PD-DATA.indication parameters

Name	Type	Valid range	Description
RxChannel	Integer	See 6.1.2	The channel on which the PPDU was received.
FCSLength	Enumeration	SHORT_FCS, LONG_FCS	The length of the FCS received as part of the PSDU. A value of SHORT_FCS indicates a 16-bit FCS, and a value of LONG_FCS indicates a 32-bit FCS.

6.2.1.3.2 When generated

6.2.1.3.3 Appropriate usage

6.2.2 PHY management service

6.2.3 PHY enumerations description

Insert the following new rows at the end of Table 25:

Table 25—PHY enumerations description

Enumeration	Value	Description
LONG_FCS		A 32 bit FCS was appended to the received PSDU.
SHORT_FCS		A 16 bit FCS was appended to the received PSDU.
UNSUPPORTED_MODE_SWITCHING		Mode switching was requested before the transmission of the PPDU, but is not a supported operation.
UNSUPPORTED_PAYLOAD_FEC		FEC coding was requested to be applied to the PHY payload, but the feature is either disabled not supported.
UNSUPPORTED_PHR_FEC		FEC coding was requested to be applied to the PHR, but the feature is either disabled or not supported.
UNSUPPORTED_TX_CHANNEL		The requested transmit channel is not supported by the current PHY configuration.

6.3 PPDU format

Change the third paragraph in 6.3 as indicated:

Each PPDU packet consists of the following basic components:

- A synchronization header (SHR), which allows a receiving device to synchronize and lock onto the bit stream
- A PHY header (PHR), which contains packet control, frame length information and, for UWB PHYs, rate, ranging, and preamble information
- A variable length payload, which, when present, carries the MAC sublayer frame (see 6.3.4)

Insert the following new paragraph after the third paragraph of subclause 6.3:

Each OFDM PPDU packet consists of the following basic components:

- A synchronization header, which consists of a Short Training Field (STF) and a Long Training Field (LTF). The STF allows a receiving device to perform automatic gain control (AGC), packet detection, de-assertion of CCA based on CCA modes (CCA Mode 1,2 or 3, as defined in 6.13.9), and coarse synchronization. The LTF allows a receiving device to do fine synchronization and perform channel estimation.

- A PHR, which contains frame data rate and frame length information. The PHR shall be encoded at the lowest data rate supported for each bandwidth option.
- A variable length PSDU, which carries the following:
  - The MAC sublayer frame (MAC Header, MAC Payload, and MAC CRC-32 as defined in 7.2),
  - Convolutional encoder tail-bits (six zeros), and
  - Zero pad-bits to extend the data fill an integer number of OFDM symbols.

Change the fourth paragraph of 6.3 as indicated:

The PPDU packet structure shall be formatted as illustrated in Figure 24, Figure 25, ~~or~~ Figure 26, Figure 26a, Figure 26b, Figure 26c, or Figure 26d. Both Figure 26a and Figure 26b apply to the MR-FSK PHY. Figure 26c applies to the MR-O-QPSK PHY. Figure 26d applies to the OFDM PHY (see 6.3.4a for details).

Insert the following new figures after Figure 26:

.

<table>
<tr><td></td><td></td><td colspan="3">Octets</td></tr>
<tr><td></td><td></td><td colspan="2">2</td><td>variable</td></tr>
<tr><td>Preamble</td><td>SFD</td><td>Packet Control
(5 bits)
(see 6.3.2a)</td><td>Frame Length
(11 bits)</td><td>PSDU</td></tr>
<tr><td colspan="2">SHR</td><td colspan="2">PHR</td><td>PHY payload</td></tr>
</table>

Figure 26a—Format of the MR-FSK PPDU

.

<table>
<tr><td></td><td></td><td colspan="2">Octets</td></tr>
<tr><td></td><td></td><td colspan="2">2</td></tr>
<tr><td>Preamble</td><td>SFD</td><td>Packet Control
(TBD bits)</td><td></td></tr>
<tr><td colspan="2">SHR</td><td colspan="2">PHR</td></tr>
</table>

Figure 26b—Format of the MR-FSK mode switching PPDU

6.3.1 Preamble field

Change the last paragraph of 6.3.1 as indicated:

Octets				
4 / 8	**1**	**2**		**variable**
Preamble	SFD	Packet Control (5 bits) (see 6.3.2b)	Frame Length (11 bits)	PSDU
SHR		PHR		PHY payload

Figure 26c—Format of the MR-O-QPSK PHY PPDU

Number of OFDM Symbols			
4	2	M	N
STF	LTF	PHR (see 6.3.4a.3)	PSDU
SHR		PHR	PHY payload

Figure 26d—Format of the OFDM PPDU

<editor’s note: need to harmonize this already-existing paragraph with whatever text we add. So far, the following paragraph has not been changed. See also doc 0738.>

Preamble lengths for ASK are expressed in equivalent octet times as the preamble for ASK is defined using a special symbol. For all PHYs except the ASK, CSS, UWB, and 950 MHz GFSK PHYs, the bits in the Preamble field shall be binary zeros. The ASK preamble format is described in 6.9.4.1. The bits in the preamble field for the 950 MHz GFSK PHY shall be "01010101010101010101010101010101."

Insert the following text into the last paragraph of 6.3.1:

The bits in the preamble field for the MR-FSK PHY shall be multiple strings of “01010101.” The preamble length shall be defined as the PIB attribute *phyPreambleRepetitions* that supports a range of values for the preamble length (i.e., number of preamble repetitions) of 4 – 1000 octets.

The Preamble field shall be replaced by the STF and LTF for the OFDM PHY. The STF is defined in 6.3.4a.1, and the LTF is defined in 6.3.4a.2.

6.3.2 SFD field

Change Table 27 (the entire table is not shown) as indicated:

Table 27—SFD field length

PHY	**Length**	
950–956 MHz GFSK[*]	1 octets	8 symbols
MR-FSK	2 octets	—

[*] As specified by IEEE 802.15.4d-2009

Change the first paragraph of 6.3.2 as indicated:

The SFD field shall not be transmitted for the OFDM PHY.

Change the second paragraph of 6.3.2 as indicated:

For all PHYs, except for the ASK, CSS, ~~and~~ UWB, MR-FSK, and OFDM PHYs, the SFD is an 8-bit field. For the ASK PHY, the SFD is defined using a special symbol. The lengths of the SFD for the ASK PHY are expressed in equivalent octet times. The SFD for all PHYs, except the ASK, MR-FSK, OFDM, and MR-O-QPSK PHYs, shall be formatted as illustrated in Figure 27. The SFD for the ASK PHY is defined in 6.9.4.2. The SFD field shall not be transmitted for the OFDM PHY.

Replace Figure 27 ***with the following new figure:***

Bits: 0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	1	1	0	0	1	0	1

Figure 27—Format of the SFD field (except for ASK, UWB, ~~and~~ CSS, MR-FSK, and MR-O-QPSK PHYs)

Insert the following new paragraphs and new tables (Table 28a, Table 28b) at the end of 6.3.2:

The MR-FSK SFD field consists of 2 bytes. The SFD used by the MR-FSK PHY shall be a 16-bit sequence selected from the list of values shown in Table 28a.

Table 28a—MR-FSK PHY SFD values

SFD value (bits 0–15)	**Indicates**
	Mandatory uncoded PHR
	Optional coded PHR

The SFD field of the MR-O-QPSK PHY shall be an 8-bit sequence selected from the list in Table 28b. In addition to boundary synchronization, the SFD serves as a mode indication mechanism for *SpreadingMode* when operating in the 915 MHz or 2450 MHz band.

Table 28b—Format of the SFD field for the MR-O-QPSK PHY

SFD value (bits 0–7)	**Indicates**
1 1 1 0 0 1 0 1	*SpreadingMode* is “DSSS” during PSDU.
0 0 0 1 1 0 1 0	*SpreadingMode* is “MDSSS” during PSDU for the 915 MHz and 2450 MHz band. Not supported for the 780 MHz and 868 MHz band.

The transmission sequence starts with LSB in the left to MSB in the right.

Insert the following new subclauses after 6.3.2 (6.3.2a-6.3.2b.3):

6.3.2a Packet Control field for MR-FSK

The Packet Control field is 5 bits in length and is shown in Figure 27a. This field controls the data rate and modulation scheme for the remaining portion of the packet, the length of the FCS, whether FEC is used (note: maybe the FEC method also), and whether data whitening is used.

Bits				
1	**1**	**1**	**1**	**1**
Mode Switching	Reserved	FCS Length	FEC	Data Whitening

Figure 27a—Format of the Packet Control field for MR-FSK

6.3.2a.1 Mode Switching subfield

A Mode Switching subfield set to zero indicates that the entire packet shall be transmitted at a single data rate and using a single modulation scheme. A value of one indicates that a mode switch shall occur according to the information contained in the canonical name.

The canonical name specifies the operating mode of the subsequent PPDU that follows the PPDU containing the Mode Switch subfield with a value of one. The canonical name is a page entry in channel page 7 or channel page 8, as shown in Figure 27b. As indicated in Figure 27b, a canonical name can be shortened from 32 bits to 8 bits to reduce overhead. The full representation is the same as the 32-bit channel page 7 or 8 definition. The 32 bits can be shorted as follows:

- Only page 7 or 8 needs to be selected; the 5-bit page can be shorted to one bit to select page 7 (0) or page 8 (1).
- The frequency band does not need to be specified, as mode switching is only supported within a given frequency band.
- Mode switching from one modulation scheme (e.g., FSK) to another modulation scheme (e.g., OFDM) is supported, and the 2-bit modulation scheme needs to be specified.
- Mode is the integer value of the new mode, where the integer value of the mode corresponds to the standard defined bit position (page 7) or the Generic PHY ID (page 8).

	Page	**Freq band**	**Mod scheme**	**Mode**
Full representation	5 bits	5 bits	2 bits	20 bits
Shortened form	1 bit*	0 bits	2 bits	5 bits

Figure 27b—Structure of the canonical name

*Only need to select page 7 or 8.

6.3.2a.2 FCS Length subfield

If the FCS Length subfield is set to zero, the FCS field (7.2.1.9) shall be 32 bits in length. If the FCS Length subfield is set to one, the FCS field shall be 16 bits in length.

6.3.2a.3 FEC subfield

Details of this subfield are TBD (FEC subgroup to provide).

6.3.2a.4 Data Whitening subfield

The Data Whitening subfield is used to indicate if data whitening of the PSDU is enabled (subfield value set to 1) or disabled (subfield value set to 0). Data whitening shall never be applied to the SHR or PHR.

6.3.2b Packet Control field for MR-O-QPSK

The Packet Control field of the MR-O-QPSK PHY is five bits in length and is shown in Figure 27c.

Bits (0–4)		
2	2	1
Parity Check	Rate Mode	Reserved

Figure 27c—Format of the Packet Control field for MR-O-QPSK

6.3.2b.1 Parity check field

Two parity bits as a function of the Rate Mode field, the Reserved field and the Frame Length field shall be transmitted.

Let $(p_0, p_1, \ldots, p_{15})$ be the bits of the PHR field, where p_0 refers to the least significant bit (transmitted first in time) and p_{15} refers to the most significant bit (transmitted last in time). The parity check entries at positions p_0 and p_1 shall satisfy the constraints shown in Equation (5) and Equation (6):

$$p_0 = p_2 \oplus p_3 \oplus p_4 \oplus p_5 \oplus p_6 \oplus p_7 \oplus p_8 \qquad (5)$$

$$p_1 = p_9 \oplus p_{10} \oplus p_{11} \oplus p_{12} \oplus p_{13} \oplus p_{14} \oplus p_{15} \qquad (6)$$

where addition is modulo-2 addition (addition over GF(2)).

6.3.2b.2 Rate Mode field

The MR-O-QPSK PHY supports up to four different PSDU rate modes within each frequency band. Table 28c shows the mapping of the bit values to the variable *RateMode*.

6.3.2b.3 Reserved field

The reserved subfield is for future usage and should be set to zero if not used.

Table 28c—Rate mode mapping of the MR-O-QPSK PHY

Bits (0–1)	RateMode
00	0
10	1
01	2
11	3

6.3.3 Frame Length field

Change the first paragraph of 6.3.3 as indicated:

The Frame Length field is 7 bits in length and specifies the total number of octets contained in the PSDU (i.e., PHY payload). For the MR-FSK, OFDM, and MR-O-QPSK PHYs, the Frame Length field is 11 bits in length. ~~It~~ The Frame Length field is a value between 0 and *aMaxPHYPacketSize* (see 6.4). Table 29 summarizes the type of payload versus the frame length value.

<editor's note: Table 29 is in the 15.4-2009 roll up doc (Table 21 in IEEE Std 802.15.4-2006). It has not been changed and so is not shown here.>

Insert the following new subclauses <decide where to add them after the structure is known>:

6.3.3a <placeholder for mode switching fields to be shown in Figure 26b>

TBD

6.3.4 PSDU field

Change the first paragraph of 6.3.4 as indicated:

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

Insert the following new paragraph after the first paragraph of 6.3.4:

If the Mode Switching subfield (see Figure 27a) of the Packet Control field (see Figure 26a) for the MR-FSK PHY is set to one, the PSDU field shall not be included in the packet. The PSDU field shall be included in the packet at all other times.

Insert after 6.3.4 the following new subclauses (6.3.4a through 6.3.4a.x):

6.3.4a Field descriptions for the OFDM PHY

The following subclauses define the fields for the OFDM PHY PPDU, as was previously shown in Figure 26d.

6.3.4a.1 Short Training field for OFDM

Frequency Domain STF:

The STF for the five scalable bandwidth OFDM options are defined by the following five tables. Table 29a shows the frequency domain representation of the STF for Option 1. The scaling factor used in the table is sqrt(104/12).

Table 29a— Frequency domain representation of Option 1 STF

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-64	0	-32	-2.9439	0	0	32	2.9439
-63	0	-31	0	1	0	33	0
-62	0	-30	0	2	0	34	0
-61	0	-29	0	3	0	35	0
-60	0	-28	0	4	0	36	0
-59	0	-27	0	5	0	37	0
-58	0	-26	0	6	0	38	0
-57	0	-25	0	7	0	39	0
-56	0	-24	2.9439	8	2.9439	40	-2.9439
-55	0	-23	0	9	0	41	0
-54	0	-22	0	10	0	42	0
-53	0	-21	0	11	0	43	0
-52	0	-20	0	12	0	44	0
-51	0	-19	0	13	0	45	0
-50	0	-18	0	14	0	46	0
-49	0	-17	0	15	0	47	0
-48	-2.9439	-16	2.9439	16	-2.9439	48	2.9439
-47	0	-15	0	17	0	49	0
-46	0	-14	0	18	0	50	0
-45	0	-13	0	19	0	51	0
-44	0	-12	0	20	0	52	0
-43	0	-11	0	21	0	53	0

Table 29a— Frequency domain representation of Option 1 STF

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-42	0	-10	0	22	0	54	0
-41	0	-9	0	23	0	55	0
-40	-2.9439	-8	2.9439	24	2.9439	56	0
-39	0	-7	0	25	0	57	0
-38	0	-6	0	26	0	58	0
-37	0	-5	0	27	0	59	0
-36	0	-4	0	28	0	60	0
-35	0	-3	0	29	0	61	0
-34	0	-2	0	30	0	62	0
-33	0	-1	0	31	0	63	0

Table 29b shows the frequency domain representation of the STF for Option 2. The scaling factor used in the table is sqrt(52/12).

Table 29b— Frequency domain representation of Option 2 STF

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-32	0	-16	-2.0817	0	0	16	2.0817
-31	0	-15	0	1	0	17	0
-30	0	-14	0	2	0	18	0
-29	0	-13	0	3	0	19	0
-28	0	-12	2.0817	4	2.0817	20	-2.0817
-27	0	-11	0	5	0	21	0
-26	0	-10	0	6	0	22	0
-25	0	-9	0	7	0	23	0
-24	-2.0817	-8	2.0817	8	-2.0817	24	2.0817
-23	0	-7	0	9	0	25	0
-22	0	-6	0	10	0	26	0
-21	0	-5	0	11	0	27	0
-20	-2.0817	-4	2.0817	12	2.0817	28	0
-19	0	-3	0	13	0	29	0
-18	0	-2	0	14	0	30	0
-17	0	-1	0	15	0	31	0

Table 29c shows the frequency domain representation of the STF for Option 3. The scaling factor used in the table is sqrt(26/6).

Table 29c— Frequency domain represent ai ton of Option 3 STF

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-16	0	-8	2.0817	0	0	8	2.0817
-15	0	-7	0	1	0	9	0
-14	0	-6	0	2	0	10	0
-13	0	-5	0	3	0	11	0
-12	2.0817	-4	2.0817	4	-2.0817	12	-2.0817
-11	0	-3	0	5	0	13	0
-10	0	-2	0	6	0	14	0
-9	0	-1	0	7	0	15	0

Table 29d shows the frequency domain representation of the STF for Option 4. The scaling factor used in the table is sqrt(14/6)

Table 29d— Frequency domain representation of Option 4 STF

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-8	0	-4	1.5275	0	0	4	1.5275
-7	0	-3	0	1	0	5	0
-6	1.5275	-2	1.5275	2	-1.5275	6	-1.5275
-5	0	-1	0	3	0	7	0

Table 29e shows the frequency domain representation of the STF for Option 5. The scaling factor used in the table is sqrt(6/2).

Table 29e— Frequency domain representation of Option 5 STF

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-4	0	-2	1.7321	0	0	2	-1.7321
-3	0	-1	0	1	0	3	0

There are four STF OFDM symbols, and the last 1/4 of the useful part of the fourth OFDM symbol is negated in the time domain. Figure 27d shows that for Options 2, 3, 4, and 5, the cyclic prefix is 1/4 of the useful part of the OFDM symbol, so there are 19 repetitions of the 1/4 STF symbol followed by the last 1/4 of the useful part of the fourth OFDM symbol which is negated in the time domain. For Option 1, the cyclic prefix is 1/8 symbol and the STF repetition is eight times per STF symbol, so there are 34 repetitions of 1/8 STF symbol in the four STF symbols followed by the last 1/4 of the useful part of the fourth OFDM symbol which is negated in the time domain.

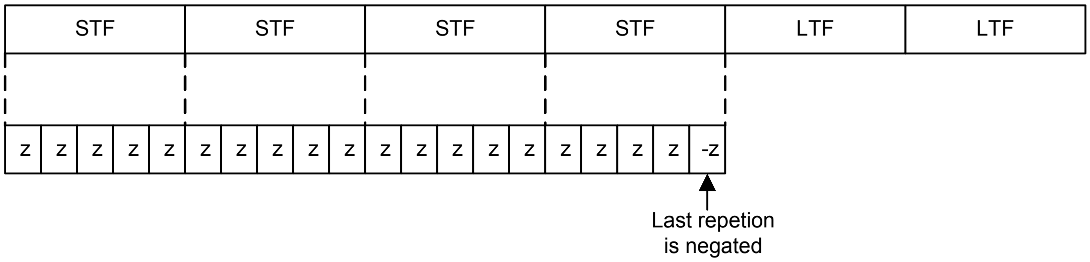


Figure 27d—Structure of STF for OFDM for Options 2, 3, 4, and 5

STF Normalization:

The STF uses lesser number of tones than the data portion. Hence, normalization of the frequency domain STF would be required to ensure that the STF power is same as the rest of the data-frame. The normalization value to have the same power as the data for OFDM symbols is sqrt(N_{active}/ (2*N_{stf})) where N_{active} is the number of used subcarriers in rest of the OFDM frame for the particular FFT option and N_{stf} is the number of subcarriers used in the STF.

Power boosting shall be applied to the STF symbols in order to aid preamble detection. The power boosting factors for each of the 5 Options is given in Table 29f.

Table 29f— Power boosting for the STF for all options

Option Number	Option 1	Option 2	Option 3	Option 4	Option 5
STF Power Boosting	TBD dB	TBD dB	TBD dB	TBD dB	TBD dB

Time Domain STF Generation:

The Time-Domain STF for Option-n (n=1,2,3,4,5) is obtained as follows:

STF_time(Option-n) = IFFT(STF_freq(Option-n)) and then the cyclic prefix is inserted before the useful part of the STF OFDM symbol

Time Domain STF Repetition:

The time-domain STF is repeated to fill four OFDM symbols with the last 1/4 symbol repetition negated before transmission.

6.3.4a.2 Long Training field for OFDM

Frequency Domain LTF:

The LTF for the five scalable bandwidth OFDM options are defined by the following five tables. Table 29g shows the frequency domain representation of the LTF for Option 1.

Table 29g— Frequency domain representation of Option 1 LTF

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-64	0	-32	-1	0	0	32	-1
-63	0	-31	-1	1	1	33	-1
-62	0	-30	-1	2	-1	34	-1
-61	0	-29	1	3	1	35	1
-60	0	-28	1	4	-1	36	1
-59	0	-27	-1	5	1	37	1
-58	0	-26	-1	6	1	38	1
-57	0	-25	-1	7	-1	39	1
-56	0	-24	-1	8	-1	40	1
-55	0	-23	-1	9	1	41	-1
-54	0	-22	1	10	-1	42	-1
-53	0	-21	1	11	1	43	-1
-52	-1	-20	-1	12	1	44	-1
-51	1	-19	1	13	1	45	-1
-50	1	-18	-1	14	1	46	-1
-49	-1	-17	-1	15	-1	47	1
-48	-1	-16	1	16	1	48	-1
-47	-1	-15	-1	17	1	49	1
-46	-1	-14	1	18	1	50	1
-45	1	-13	1	19	1	51	-1
-44	1	-12	1	20	1	52	1
-43	-1	-11	1	21	-1	53	0

Table 29g— Frequency domain representation of Option 1 LTF

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-42	-1	-10	-1	22	1	54	0
-41	1	-9	-1	23	-1	55	0
-40	1	-8	1	24	1	56	0
-39	1	-7	1	25	-1	57	0
-38	-1	-6	-1	26	1	58	0
-37	-1	-5	1	27	-1	59	0
-36	1	-4	1	28	1	60	0
-35	1	-3	-1	29	1	61	0
-34	-1	-2	1	30	-1	62	0
-33	-1	-1	1	31	1	63	0

Table 29h shows the frequency domain representation of the LTF for Option 2.

Table 29h— Frequency domain representation of Option 2 LTF

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-32	0	-16	1	0	0	16	1
-31	0	-15	-1	1	1	17	-1
-30	0	-14	1	2	-1	18	-1
-29	0	-13	1	3	1	19	-1
-28	0	-12	-1	4	1	20	-1
-27	0	-11	-1	5	-1	21	-1
-26	-1	-10	-1	6	1	22	1
-25	-1	-9	1	7	-1	23	-1
-24	-1	-8	1	8	-1	24	-1
-23	-1	-7	-1	9	1	25	-1
-22	1	-6	1	10	-1	26	1
-21	1	-5	1	11	1	27	0
-20	1	-4	1	12	1	28	0
-19	-1	-3	-1	13	-1	29	0
-18	1	-2	-1	14	-1	30	0
-17	-1	-1	-1	15	1	31	0

Table 29i shows the frequency domain representation of the LTF for Option 3.

Table 29i— Frequency domain representation of Option 3 LTF

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-16	0	-8	1	0	0	8	-1
-15	0	-7	1	1	-1	9	1
-14	0	-6	1	2	-1	10	1
-13	1	-5	1	3	1	11	-1
-12	-1	-4	1	4	-1	12	-1
-11	1	-3	1	5	1	13	1
-10	-1	-2	1	6	1	14	0
-9	1	-1	-1	7	-1	15	0

Table 29j shows the frequency domain representation of the LTF for Option 4.

Table 29j— Frequency domain representation of Option 4 LTF

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-8	0	-4	1	0	0	4	1
-7	1	-3	-1	1	-1	5	-1
-6	-1	-2	1	2	1	6	-1
-5	1	-1	1	3	1	7	-1

Table 29k shows the frequency domain representation of the LTF for Option 5.

Table 29k— Frequency domain representation of Option 5 LTF

Tone#	Value	Tone#	Value	Tone#	Value	Tone#	Value
-4	0	-2	1	0	0	2	1
-3	1	-1	1	1	-1	3	-1

Time Domain LTF Generation:

The Time-Domain LTF for Option-n (n=1,2,3,4,5) is obtained as follows:

LTF_time(Option-n) = IFFT(LTF_freq(Option-n)) and then the cyclic prefix is inserted before the useful part of the LTF OFDM symbol

LTF Normalization

Power boosting shall be applied to the LTF symbols over the power of the data OFDM symbols. The power boosting factors for the LTF for each of the 5 Options is given in Table 29l.

Table 29l— Power boosting for the LTF for all options

Option Number	**Option 1**	**Option 2**	**Option 3**	**Option 4**	**Option 5**
LTF Power Boosting	TBD dB	TBD dB	TBD dB	TBD dB	TBD dB

Time Domain LTF Repetition:

The time-domain LTF is repeated to fill two OFDM symbols (240 us) before transmission.

6.3.4a.3 PHY Header for OFDM

The PHY Header (PHR) field consists of the Frame Length field and frame control bits. It is encoded using the lowest data rate in each OFDM bandwidth option for robustness. The list of data rates for each OFDM bandwidth option can be found in 6.12b.1.

The PHR field structure shall be formatted as illustrated in Figure 27e.

Rate (5 bits)	Reserved (1 bit)	Frame Length (11 bits)	Reserved (2 bits)	Scrambler (2 bits)	Reserved (1 bit)	HCS (8 bits)	Tail (6 bits)

Figure 27e—PHY header fields for OFDM

The PHY header fields include:

- Rate field specifies the data rate of the payload frame (5 bits)
- One reserved bit after the Rate field
- Frame Length field specifies the length of the payload (11 bits)
- Two reserved bits after the Frame Length field
- Scrambler field specifies the scrambling seed (2 bits)
- One reserved bit after the Scrambler field
- Header Check Sequence (HCS) 8-bit CRC taken over the data fields only
- Six tail bits, which are all zeros, for Viterbi decoder flushing

All reserved bits shall be set to zero.

The PHY header occupies three OFDM symbols for Option 1 and six OFDM symbols for Options 2, 3, 4, and 5. The PHY header shall be transmitted using the lowest supported MCS level for the option being used. The PHY header is sent to the convolutional encoder from left to right starting with the first rate bit.

6.4 PHY constants and PIB attributes

6.4.1 PHY constants

Change Table 30 (the entire table is not shown) as indicated:

Table 30—PHY constants

Constant	Description	Value
aMaxPHYPacketSize	The maximum PSDU size (in octets) the PHY shall be able to receive.	2047 for SUN PHYs 127 for all other PHYs
aMRFSKSFDLength	The length of the SFD, in octets, for the MR-FSK PHY.	2
aMRFSKPHRLength	The length of the PHR, in octets, for the MR-FSK PHY.	2
aSUNTurnaroundTime	RX-to-TX or TX-to-RX maximum turnaround time (in milliseconds) (see 6.13.1 and 6.13.2).	1

6.4.2 PHY PIB attributes

Change Table 31 (the entire table is not shown) as indicated:

Table 31—PHY PIB attributes

Attribute	Identifier	Type	Range	Description
phyCurrentChannel	0x00	Integer	0–511	The RF channel to use for all following transmissions and receptions (see 6.1.2).
phyCurrentSUNPageEntry		Bit Map	32 bits	Defines the current frequency band, modulation scheme, and particular PHY mode when *phyCurrentPage* = 7 or 8. It is a 32-bit field per the page 7 or page 8 definitions, but only one bit in the 20-bit PHY Mode field will be set to indicate the current mode. If it is a page 7 entry, the set bit indicates the particular standard defined PHY mode. If it is a page 8 entry, the set bit indicates the index or ID in the *phyGenericPHYDescriptors* array used to define the current PHY mode.

Table 31—PHY PIB attributes

Attribute	Identifier	Type	Range	Description
phyGenericPHYDescriptors		Array	An array sized by *phyNumGenericPHYDescriptors*. The size of each element is per the GenericPHYDescriptor entry (see Table 31a).	A table of GenericPHYDescriptor entries, where each entry is used to define a page 8 PHY mode.
phyMaxFrameDuration†	0x05	Integer	55, 212, 266, 1064 except UWB, ~~and~~ CSS, and MR-FSK PHYs	The maximum number of symbols in a frame, except for UWB, ~~and~~ CSS, and SUN PHYs: = *phySHRDuration* + ceiling([*aMaxPHYPacketSize* + 1] × *phySymbolsPerOctet*) For UWB PHYs, see 6.4.2.1. For CSS PHYs, one of two values depending on data rate. See 6.4.2.2. For MR-FSK PHY (uncoded frames): = *phySHRDuration* + (*aMRFSKPHRLength* + *aMaxPHYPacketSize*) × *phySymbolsPerOctet*.
phyMaxSUNChannelSupported		Integer	0–511	The page 7 or page 8 entry specified by *phyCurrentSUNPageEntry* describes the total number of defined channels for the PHY mode, where there are either a standard defined number of channels (page 7) or a Generic PHY defined number of channels (page 8). *phyMaxSUNChannelSupported* defines the highest channel number supported by the device and is used to size the *phySUNChannelsSupported* array. *phyMaxSUNChannelSupported* is only valid if *phyCurrentPage* equals 7 or 8.
phyNumGenericPHYDescriptors		Integer	0–20	The number of GenericPHYDescriptor entries supported by the device.
phyNumSUNPageEntriesSupported		Integer	0–63	The number of SUN page entries supported.

Table 31—PHY PIB attributes

Attribute	Identifier	Type	Range	Description
phySHRDuration†	0x06	Integer	3, 7, 10, 40 except UWB, ~~and~~ CSS, and MR-FSK PHYs. For UWB PHYs see 6.4.2.1 For CSS PHY, 12, 24.	The duration of the synchronization header (SHR) in symbols for the current PHY. For CSS PHY, a value of 12 corresponds to 1 Mb/s and 24 corresponds to 250 kb/s. For MRFSK PHY:= *phySymbolsPerOctet* × (*phyPreambleRepetitions* + *aMRFSKSFDLength*).
phySUNChannelsSupported		Bit Map	*phyMaxSUNChannelSupported*/8 octets or *phyMaxSUNChannelSupported*+1 bits	The channel bit map identifying which channels may be used when *phyCurrentPage* = 7 or 8. Bit zero in the first byte corresponds to channel 0, and bit seven in the first byte corresponds to channel 7. Bit zero in the second byte corresponds to channel 8, and bit seven in the second byte corresponds to channel 15, etc. A bit is set (=1) to indicate the channel is available, and a bit is clear (=0) to indicate the channel is unavailable.
phySUNPageEntriesSupported		Array	An R x 32-bit array, where R ranges from 0 to *phyNumSUNPageEntriesSupported*	Each row is a 32-bit element defining a supported SUN page 7 or 8 entry. The 32 bits are per the page 7 and page 8 “channel page” definitions.
phySymbolsPerOctet	0x07	Float	0.4, 1.3, 1.6, 2, 4, 5.3, 8	The number of symbols per octet for the current PHY. For UWB PHYs, see 6.4.2.1. For CSS PHYs, 4/3 corresponds to 1 Mb/s and 32/6 corresponds to 250 kb/s.
phyPreambleSymbolLength	0x08	Integer	1 or 0 for UWB PHY. See description for MR-FSK PHY.	For the UWB PHY, 0 indicates preamble symbol length is 31, 1 indicates that length 127 symbol is used. ~~Present for UWB PHY.~~ For the MR-FSK PHY:= *phyPreambleRepetitions* × *phySymbolsPerOctet*.
phyPreambleRepetitions		Integer	4–1000	The number (in octets) of preamble repetitions.
phyScramblePSDU		Boolean	TRUE or FALSE	A value of FALSE indicates that data whitening of the PSDU is disabled. A value of TRUE indicates that data whitening of the PSDU is enabled.

Insert the following new table (Table 31a) after Table 31:

Table 31a—Elements of GenericPHYDescriptor

Attribute	Identifier	Type	Range	Description
Id		Integer	0–19	An identifier of the Generic PHY mode. This ID corresponds to a bit position (0–19) in the page 8 channel page definition.
FirstChannelFrequency		Integer	All bands	Specifies the center frequency, in hertz, of the first channel in the list.
NumChannels		Integer	0–511	The number of channels defined for the particular PHY mode. The actual channels supported by the device are defined by *phySUNChannelsSupported.*
ChannelSpacing		Integer	1–1,000,000	The channel spacing (distance between adjacent center frequencies) in hertz.
DataRate		Integer	1–1,000,000	The data rate in bps.
ModulationScheme		Enumeration	0 = FSK/GFSK 1 = OFDM 2 = O-QPSK 3 = reserved NOTE — if specific parameters are not defined for the other modulation schemes, values 1–3 will be left as reserved.	The modulation scheme of the Generic PHY entry. The remaining Generic PHY parameters are determined based on the modulation scheme.
FSKModulationOrder		Enumeration	0 = 2-level FSK 1 = 4-level FSK	The FSK modulation order.
FSKModulationIndex		Float	0.25–2.50	The FSK modulation index.
FSKBT		Enumeration	0 = 0.5 1 = 1.0	The FSK BT. The value is 0.5 for GFSK or 1.0 for FSK.

6.5 2450 MHz PHY specifications

6.6 2450 MHz PHY chirp spread spectrum (CSS) PHY

6.7 868/915/950 MHz band binary phase-shift keying (BPSK) PHY specifications

6.8 780 MHz band (optional) O-QPSK PHY specifications

6.9 868/915 MHz band (optional) amplitude shift keying (ASK) PHY specifications

6.10 868/915 MHz band (optional) O-QPSK PHY specifications

6.11 950 MHz band Gaussian frequency-shift keying (GFSK) PHY specifications

6.12 UWB PHY specification

Insert after 6.12.15.3 the following new subclauses (6.12a through 6.12c.6.4):

6.12a MR-FSK PHY specification

<editor’s note: “optional” behavior should be described in 6.12a.x (see comment 41 in 15-10-0031).>

6.12a.1 Modulation and coding

The possible modulation types for the MR-FSK PHY are FSK and GFSK, and the modulation order may be either two or four. The generic PHY mechanism also allows other modulation schemes to be supported.

6.12a.1.1 Reference modulator diagram

The functional block diagram for the MR-FSK reference modulator is shown in Figure 65a.

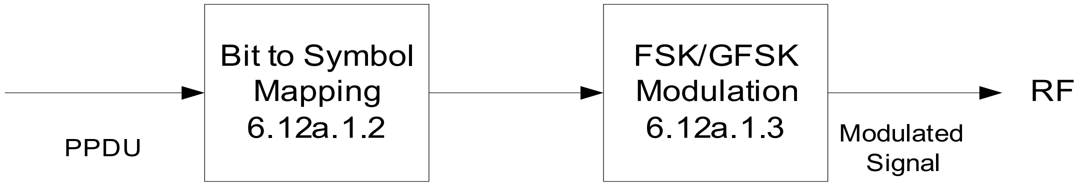


Figure 65a—Reference reference modulator diagram

6.12a.1.2 Bit-to-symbol mapping

The nominal frequency deviation, Δf, shall be the symbol rate * modulation index / 2. For 2-level FSK/GFSK modulation, symbol '0' shall be modulated on -Δf and symbol '1' shall be modulated on +Δf. For 4-level FSK/GFSK modulation, two bits shall be mapped to each symbol. The symbol encoding for both 2-level and 4-level FSK/GFSK modulation is shown in Table 75a.

Table 75a—MR-FSK symbol encoding

2FSK/GFSK	
Symbol (binary)	Deviation * Δf
0	-1
1	+1
4FSK/GFSK	
Symbol (binary)	Deviation * Δf
10	+3
11	+1
01	-1
00	-3

6.12a.1.3 FSK/GFSK modulation

6.12a.1.4 Forward error correction (FEC)

Support for forward error correction is optional. The details of the FEC algorithm are TBD.
<need to work in text that was formerly in 6.3: "Support for uncoded header and uncoded payload is mandatory; support for coded header/payload is optional.">

6.12a.2 Data whitening

Support for data whitening is optional.

When data whitening is enabled at the transmitter, the Data Whitening subfield of the Packet Control field shall be set to one (see 6.3.2a.4), and the scrambled data shall be the exclusive or (XOR) of the PSDU with the PN9 sequence, as described by Equation (7).

$$E_n = R_n \oplus \mathrm{PN9}_n \qquad (7)$$

where

E_n is the whitened bit
R_n is the data bit being whitened
$\mathrm{PN9}_n$ is PN9 sequence

For each packet transmitted with data whitening enabled, R_0 is the first bit of the PSDU and the index *n* increments for subsequent bits of the PSDU.

For packets received with the Data Whitening subfield of the Packet Control field set to one, the receiver decodes the scrambled data, as described by Equation (8).

$$R_n = RE_n \oplus \mathrm{PN9}_n \qquad (8)$$

The PN generator is defined by the schematic in Figure 65b.

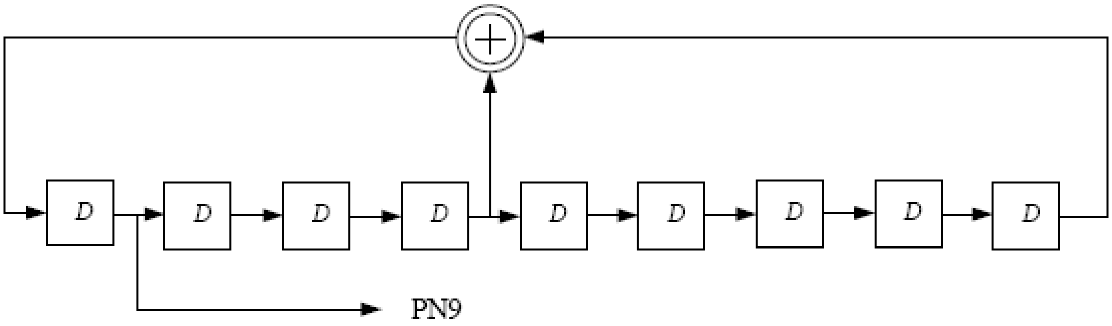


Figure 65b—Schematic of the PN generator

The seed in the PN9 shall be all ones: "111111111." The PN9 shall be reinitialized to the seed after each packet (either transmit or receive).

The PN9 generator is clocked starting from the seed. For example, the first 30 bits out of the PN9, once it is enabled, would be as follows:

$PN9_n = 0_0, 0_1, 0_2, 0_3, 1_4, 1_5, 1_6, 1_7, 0_8, 1_9, 1_{10}, 1_{11}, 0_{12}, 0_{13}, 0_{14}, 0_{15}, 1_{16}, 0_{17}, 1_{18}, 1_{19}, 0_{20}, 0_{21}, 1_{22}, 1_{23}, 0_{24}, 1_{25}, 1_{26}, 0_{27}, 1_{28}, 1_{29}$.

In the transmitter, the bits after the PHR are obtained by an XOR function that has the PN9 at its first input and the data at its second input. The preamble, SFD, PHR, and the output of the XOR function are applied to the FSK or GFSK modulator.

In the receiver, the bits after the PHR are obtained by an XOR function that has the PN9 at its first input and the received bits from the FSK or GFSK demodulator at its second input. The preamble, SFD, PHR, and the output of the XOR function are the received data.

6.12a.3 Frequency hopping modes (optional)

TBD

6.12a.4 Packet timestamping

TBD

6.12a.5 Radio specification

Table 75b contains parameters specific to the MR-FSK PHY.

6.12b OFDM PHY specification

6.12b.1 Data rates

There are five OFDM options with five different recommended FFT sizes of 128, 64, 32, 16, and 8.

A device implementing the OFDM PHY shall support one or several of the data rates shown in Table 75c:

Table 75b—MR-FSK radio parameters

Parameter	Value
Modulation index range	±20%
Frequency tolerance/stability	±20 ppm
System time stability	±20 ppm
TX amplifier rise time	≤ 100µs
Channel switch time	≤ 500µs
Receiver sensitivity	–90dBm
Adjacent channel rejection	10dB
Alternate channel rejection	30dB
Symbol rate tolerance	±20 ppm

Table 75c—Data Rates for OFDM PHY

Parameter	OFDM Option 1	OFDM Option 2	OFDM Option 3	OFDM Option 4	OFDM Option 5	Unit
FFT size	128	64	32	16	8	
Active tones	104	52	26	14	6	
# Pilot tones	8	4	2	2	2	
# Data tones	96	48	24	12	4	
MCS0 (BPSK rate 1/2 with 4x frequency repetition)	100	50				kbps
MCS1 (BPSK rate 1/2 with 2x frequency repetition)	200	100	50			kbps
MCS2 (QPSK rate 1/2 and 2x frequency repetition)	400	200	100	50		kbps
MCS3 (DCM QPSK rate 1/2)	800	400	200	100		kbps
MCS4 (QPSK rate 1/2)	800	400	200	100		kbps
MCS5 (DCM QPSK rate 3/4)		600	300	150	50	kbps
MCS6 (QPSK rate 3/4)		600	300	150	50	kbps
MCS7 (16-QAM rate 1/2)		800	400	200	66 and 2/3	kbps
MCS8 (16-QAM rate 3/4)			600	300	100	kbps

6.12b.2 Data transfer

6.12b.3 Modulation and coding

6.12b.3.1 Reference modulator diagram

(Figure 65c) [Editor's note: STS-Time Domain block should be changed to STF Frequency Domain, and LTS Frequency Domain should be changed to LTF Frequency domain. Also puncturer bypass should be removed.]

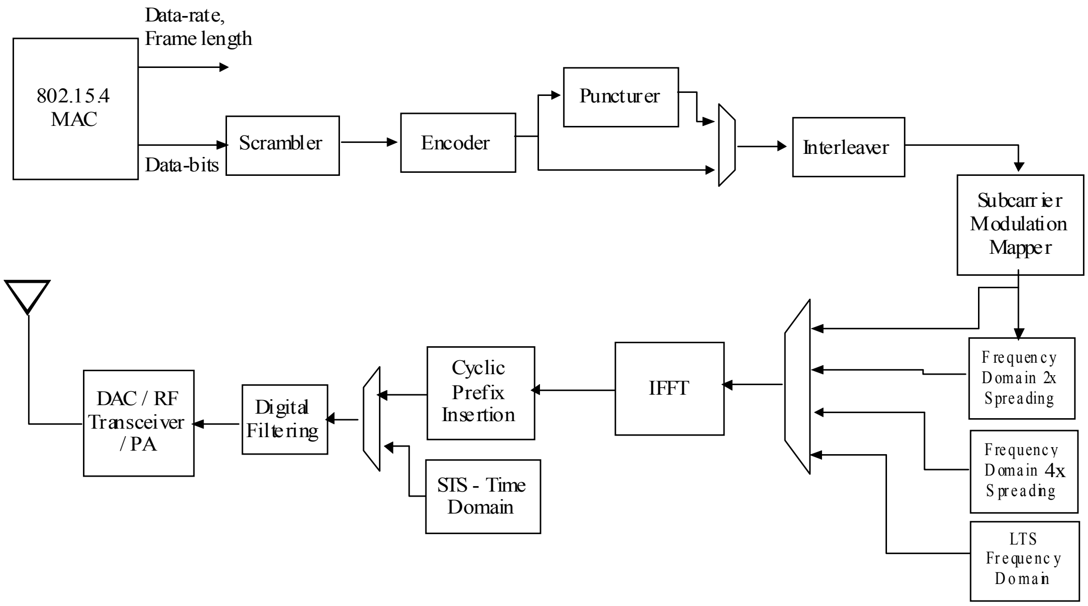


Figure 65c—Reference modulator diagram for OFDM

6.12b.3.2 Bit-to-symbol mapping

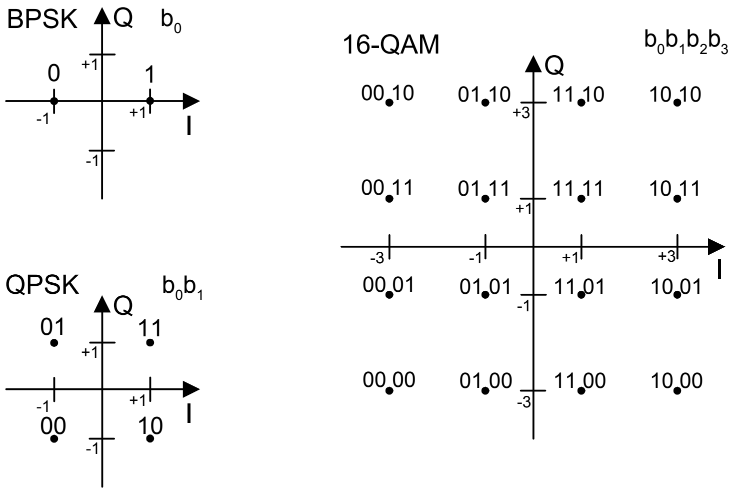


Figure 65d—Bit to symbol mapping for OFDM

For BPSK, b0 determines the I value, as illustrated in Table 75d. For QPSK, b0 determines the I value and b1 determines the Q value, as illustrated in Table 75e. For 16-QAM, b0b1 determines the I value and b2b3 determines the Q value, as illustrated in Table 75f.

The output values, d, are formed by multiplying the resulting (I+jQ) value by a normalization factor K_{MOD}, as described in Equation (9).

$$d = (I + jQ) \times K_{MOD} \quad (9)$$

The normalization factor, K_{MOD}, depends on the base modulation mode, as prescribed in Table 75g. The purpose of the normalization factor is to achieve the same average power for all mappings.

Table 75d—BPSK encoding table

Input bit (b_0)	I-out	Q-out
0	-1	0
1	1	0

Table 75e—QPSK encoding table

Input bit (b_0)	I-out
0	-1
1	1

Input bit (b_1)	Q-out
0	-1
1	1

Table 75f—16-QAM encoding table

Input bits (b_0 b_1)	I-out
00	-3
01	-1
11	1
10	3

Input bits (b_2 b_3)	Q-out
00	-3
01	-1
11	1
10	3

Table 75g—Modulation-dependent normalization factor K_{MOD}

Modulation	K_{MOD}
BPSK	1
QPSK	1/sqrt(2)
16-QAM	1/sqrt(10)

For dual-carrier modulation (DCM), the coded and interleaved binary serial input data, $b[i]$ where $i = 0, 1, 2, \ldots$, shall be divided into groups of 4N bits and converted into 2N complex numbers using a technique called dual-carrier modulation. N is the number of data tones in one-half of the subcarriers. The conversion shall be performed as follows:

1) The 4N coded bits are grouped into N groups of four bits. Each group is represented as ($b[g(k)]$, $b[g(k)+1]$, $b[g(k) + \mathrm{N}]$, $b[g(k) + \mathrm{N}+1]$), where $k \in [0, \mathrm{N}-1]$ and

$$g(k) = \begin{cases} 2k & k \in \left[0, \dfrac{N}{2} - 1\right] \\ 2k + N & k \in \left[\dfrac{N}{2}, N - 1\right] \end{cases} \tag{10}$$

2) Each group of four bits ($b[g(k)]$, $b[g(k)+1]$, $b[g(k) + \mathrm{N}]$, $b[g(k) + \mathrm{N}+1]$) shall be mapped onto a four-dimensional constellation, as shown in the figure below, and converted into two complex numbers ($d[k]$, $d[k + \mathrm{N}]$). The mapping between bits and constellation is enumerated in the table below.

3) The complex numbers shall be normalized using a normalization factor K_{MOD}.

The normalization factor $K_{MOD} = 1/\sqrt{10}$ is used for the dual-carrier modulation. In practical implementations, an approximate value of the normalization factor can be used, as long as the device conforms to the modulation accuracy requirements.

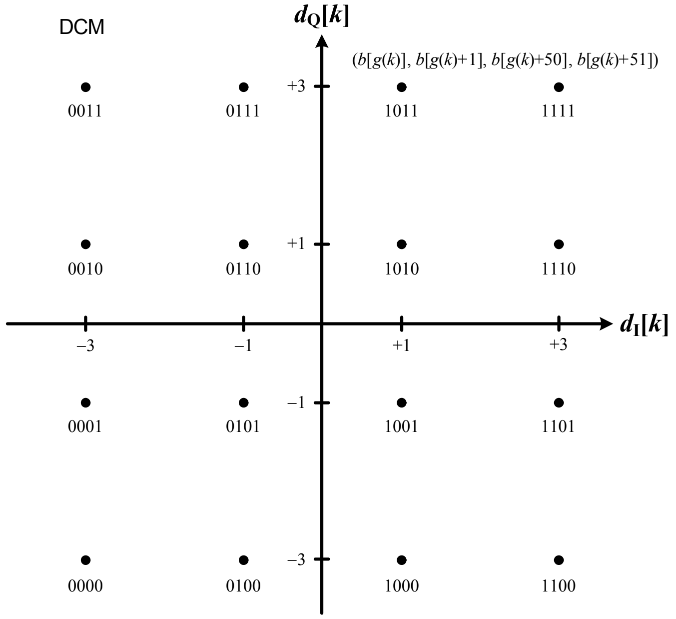


Figure 65e—DCM mapping for d[k]

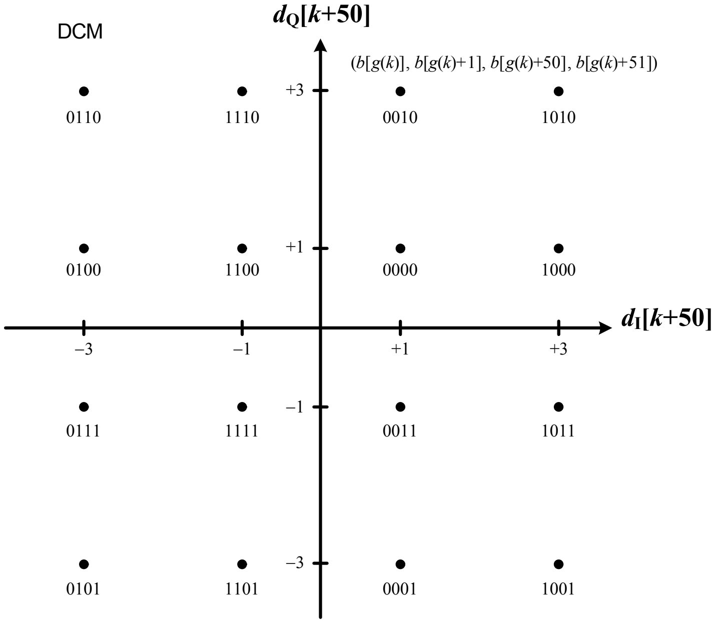


Figure 65f—DCM mapping for d[k+N]

Table 75h—Dual Carrier Modulation Encoding Table

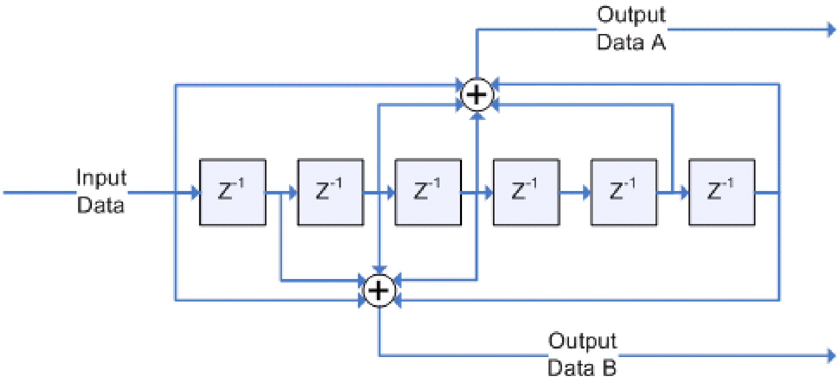
Input Bit ($b[g(k)]$, ($b[g(k)+1]$, ($b[g(k)+N)]$, ($b[g(k)+N+1]$)	**$d[k]$ *I*-out**	**$d[k]$ *Q*-out**	**$d[k+N]$ *I*-out**	**$d[k+N]$ *Q*-out**
0000	-3	-3	1	1
0001	-3	-1	1	-3
0010	-3	1	1	3
0011	-3	3	1	-1
0100	-1	-3	-3	1
0101	-1	-1	-3	-3
0110	-1	1	-3	3
0111	-1	3	-3	-1
1000	1	-3	3	1
1001	1	-1	3	-3
1010	1	1	3	3
1011	1	3	3	-1
1100	3	-3	-1	1
1101	3	-1	-1	-3
1110	3	1	-1	3
1111	3	3	-1	-1

6.12b.3.3 Modulation parameters

6.12b.3.4 Forward error correction (FEC)

The DATA field, composed of PSDU, tail, and pad parts, shall be coded with a convolutional encoder of coding rate R = 1/2 or 3/4, corresponding to the desired data rate. The convolutional encoder shall use the industry-standard generator polynomials, $g_0 = 133$ and $g_1 = 171$, of rate R = 1/2, as shown in Table 65g.

The device shall support also coding rates of R=3/4, derived by puncturing, as shown in Figure 65h:



Convolutional Encoder: Rate ½, constraint length K=7
Generator polynomials [133, 171]

Figure 65g—Rate 1/2 convolutional encoder

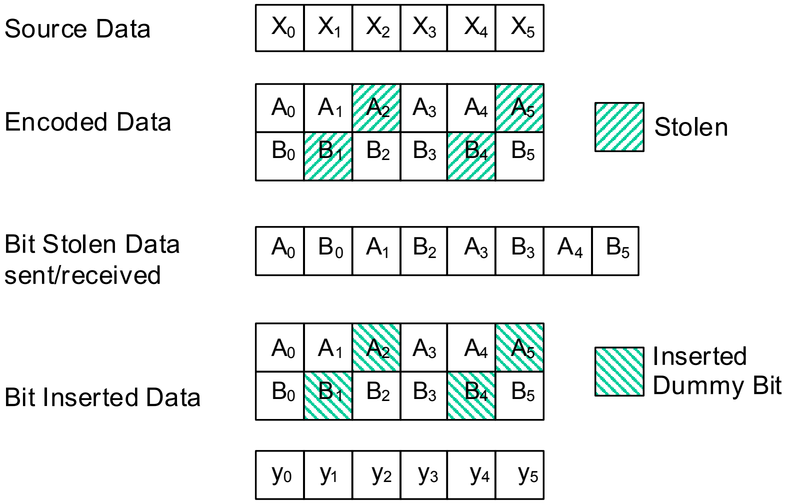


Figure 65h—Puncturing for rate 3/4

6.12b.3.5 Interleaver

The interleaving is defined for each one of the five OFDM options, through the following Matlab scripts:

i = (Ncbps/Nrow)(k mod Nrow) + floor(k/Nrow), k = 0, 1, 2, … Ncbps -1

j = s*floor(i/s) + (i + Ncbps - floor(Nrow*i/Ncbps)) mod s, i = 0, 1, 2, …, Ncbps

s = max(Nbpsc/2, 1) where Nbpsc => (BPSK =1, QPSK= 2, 16QAM = 4)

OFDM Option 1:

Ncbps = 96*{1,2}

Nrow = 12

OFDM Option 2:

Ncbps = 48*{1,2,4}

Nrow = 12

OFDM Option 3:

Ncbps = 24*{1,2,4}

Nrow = 12

OFDM Option 4:

Ncbps = 12*{1,2,4}

Nrow = 12

OFDM Option 5:

Ncbps = 6*{1,2,4}

Nrow = 12

6.12b.3.6 Frequency spreading

Frequency spreading by 2x

Frequency spreading is a method of replicating PSK symbols on different carriers

The device shall offer the possibility to create a 2x repetition through frequency spreading.

The spreading is performed by first separating out the data tones from the pilot tones. The data tones are re-numbered from $-N_d/2$ to -1 and 1 to $N_d/2$, where N_d is the number of data tones in an OFDM symbol. As an example with Option 3 there are two pilot tones and 24 data tones with indices from -13 to 13 excluding the DC tone, so the data tones are re-numbered as d_{-12}, d_{-11}, d_{-10}, d_{-9}, d_{-8}, d_{-7}, d_{-6}, d_{-5}, d_{-4}, d_{-3}, d_{-2}, d_{-1}, and d_1,d_2, d_3, d_4, d_5, d_6, d_7, d_8, d_9, d_{10}, d_{11}, d_{12}, . The DC tone is omitted since it is not used in any of the OFDM Options.

The data tones to be transmitted in the OFDM symbol are placed into the positive data tones (numbered from 1 to $N_d/2$). In order to reduce the peak-to-average power ratio of the OFDM symbol with frequency spreading, after copying the data tones to the negative frequencies phase rotations are applied.

$d_{k-(Nd/2)-1} = d_k$ exp(j*2*pi*(2*k-1)/4) for k = 1 to $N_d/2$

Frequency spreading by 4x

As with frequency spreading by 2x, first the data tones are separated from the pilot tones and are re-numbered. The data tones to be transmitted in the OFDM symbol are placed into the lower half of the positive data tones (numbered from 1 to $N_d/4$). In order to reduce the peak-to-average power ratio of the OFDM symbol with frequency spreading, after copying the data tones to the negative frequencies phase rotations are applied.

$d_{k+(Nd/4)} = d_k$ exp(j*2*pi*(k-1)/4) for k = 1 to $N_d/4$

$d_{k-(Nd/2)-1} = d_k$ exp(j*2*pi*(2*k-1)/4) for k = 1 to $N_d/4$

$d_{k-(Nd/4)-1} = d_k$ exp(j*2*pi*(3*k-1)/4) for k = 1 to $N_d/4$

6.12b.3.7 Pilot Tones / Null Tones

The pilot tones and null tones are defined as shown in Table 75i:

Table 75i—Number of Pilot and Null Tones for OFDM PHY

	OFDM Option 1	OFDM Option 2	OFDM Option 3	OFDM Option 4	OFDM Option 5
Active tones	104	52	26	14	6
# Pilot tones	8	4	2	2	2
# Data tones	96	48	24	12	4
#DC null tones	1	1	1	1	1

The pilot tones shall be transmitted with different shifts in the frequency domain in order to enable channel estimation when the channel is changing due to Doppler. Immediately after the second LTF, the pilot shifts change every three OFDM symbols to another set. For Options 1, 2, and 3, there are three sets of pilot shifts defined per option, and for Options 4 and 5, there are two sets of pilot shifts defined per option.

Figure 66 illustrates how the pilot sets cycle through Sets 1, 2, and 3. This is valid for Options 1, 2, and 3, since these Options all have three pilot sets. The pilot sets for each Option are unique to that Option. The long vertical lines show visually when each cycle through the sets is complete.

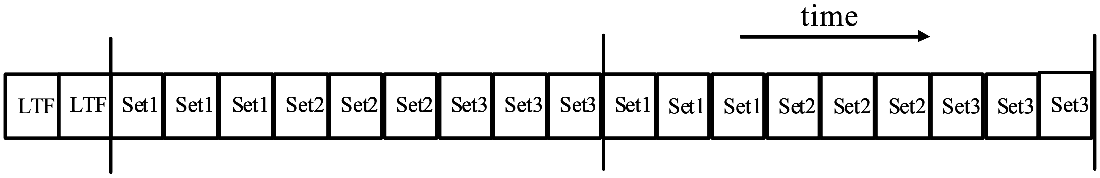


Figure 65i—Pilot tone sets for Options 1, 2, and 3.

Figure 65j illustrates how the pilot sets cycle through Sets 1 and 2. This is valid for Options 4 and 5, since these options both have two pilot sets.

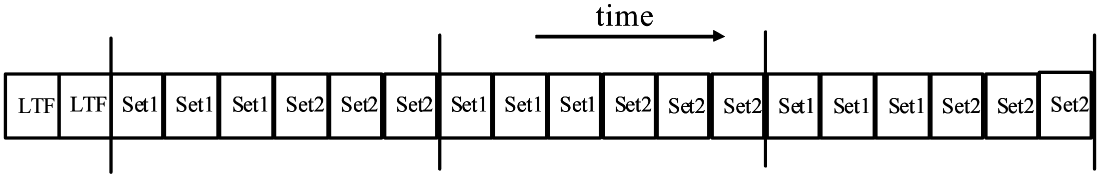


Figure 65j—Pilot tone sets for Options 4 and 5.

For Option 1, the device shall use three sets of pilot tones:

The subcarriers for pilot/data are numbered as -52 to 52 with the DC unused

Pilot Set 1: -46 -33 -19 -6 6 19 33 46

Pilot Set 2: -50 -37 -24 -11 2 15 28 41

Pilot Set 3: -41 -28 -15 -2 11 24 37 50

For Option 2, the device shall use three sets of pilot tones:

The subcarriers for pilot/data are numbered as -26 to 26 with the DC unused

Pilot Set 1: -20 -6 6 20

Pilot Set 2: -24 -11 2 15

Pilot Set 3: -15 -2 11 24

For Option 3, the device shall use three sets of pilot tones:

The subcarriers for pilot/data are numbered as -13 to 13 with the DC unused

Pilot Set 1: -7 7

Pilot Set 2: -11 2

Pilot Set 3: -2 11

For Option 4, the device shall use two sets of pilot tones:

The subcarriers for pilot/data are numbered as -7 to 7 with the DC unused

Pilot Set 1: -6 -2

Pilot Set 2: 2 6

For Option 5 the device shall use two sets of pilot tones:

The subcarriers for pilot/data are numbered as -3 to 3 with the DC unused

Pilot Set 1: -3 1

Pilot Set 2: -1 3

The data carried on the pilot tones shall be determined by a pseudo-noise sequence PN9 with the seed "111111111." The first output bit is assigned to most negative index in Set 1. For example, for Option 3, the first output bit from the PN9 sequence is assigned to the pilot symbol with index -7 and the second output bit is assigned to the pilot symbol with index 7. Table 75j shows the mapping from PN9 bits to the pilot BPSK symbols. Index n starts after the LTF from zero and is increased by one every pilot subcarrier.

Table 75j—Mapping from PN9 sequence to Pilot BPSK Symbols

Input bit ($PN9_n$)	BPSK symbol
-1	0
1	1

6.12b.3.8 Cyclic Prefix

A cyclic prefix shall be inserted before each OFDM symbol. The duration of the cyclic prefix shall be 1/8 of the useful part of the OFDM symbol (40/3 µs which can also be written as 13 and 1/3 µs) except for the STF for Options 2, 3, 4, and 5 where the cyclic prefix shall be 1/4 of the useful part of the OFDM symbol (80/3 µs which can also be written as 26 and 2/3 µs). The cyclic prefix is a replication of the last part of the useful part of the OFDM symbol.

6.12b.3.9 PPDU Tail Bit Field (TAIL)

The PPDU tail bit field shall be six bits of "0," which are required to return the convolutional encoder to the "zero state." This procedure improves the error probability of the convolutional decoder, which relies on future bits when decoding and which may be not be available past the end of the message. The PLCP tail bit field shall be produced by replacing six scrambled "zero" bits following the message end with six nonscrambled "zero" bits.

6.12b.3.10 Pad Bits (PAD)

The number of bits in the DATA field shall be a multiple of N_{CBPS}, the number of coded bits in an OFDM symbol (24, 48, 96, or 192 bits for Option 1; 24, 48, 96, or 192 bits for Option 2; 12, 24, 48,or 96 bits for Option 3; 12, 24, or 48 bits for Option 4; 8 or 16 bits for Option 5). To achieve that, the length of the message is extended so that it becomes a multiple of N_{DBPS}, the number of data bits per OFDM symbol. At least six bits are appended to the message, in order to accommodate the TAIL bits, as described in 6.12b.3.9. The number of OFDM symbols, N_{SYM}; the number of bits in the DATA field, N_{DATA}; and the number of pad bits, N_{PAD}, are computed from the length of the PSDU (LENGTH) as follows:

N_{SYM} = Ceiling ((8 × LENGTH + 6)/N_{DBPS})

$N_{DATA} = N_{SYM} \times N_{DBPS}$

$N_{PAD} = N_{DATA} - (8 \times \text{LENGTH} + 6)$

The function ceiling (.) is a function that returns the smallest integer value greater than or equal to its argument value. The appended bits (“pad bits”) are set to “zeros” and are subsequently scrambled with the rest of the bits in the DATA field.

6.12b.3.11 Pulse shape

6.12b.4 Radio specification

6.12b.4.1 Transmit PSD Mask

The OFDM transmit PSD mask is TBD.

6.12b.4.2 Receiver minimum input level sensitivity

The PER shall be less than 10% at a PSDU length of 250 bytes for rate-dependent input levels shall be the numbers listed in a table below which is TBD. The minimum input levels are measured at the antenna connector (NF is TBD and TBD dB implementation margins are assumed).

6.12b.4.3 Adjacent channel rejection

The adjacent channel rejection for OFDM is TBD.

6.12b.4.4 Alternate adjacent channel rejection

The alternate adjacent channel rejection for OFDM is TBD.

6.12c MR-O-QPSK specification

The MR-O-QPSK PHY is a multi-regional and multi-rate PHY supporting the following independent bands of operation:

- the Chinese frequency band 779–787 MHz
- the European frequency band 868–870 MHz
- the ISM band 902–928 MHz
- the ISM band 2400–2483.5 MHz.

The MR-O-QPSK PHY supports multiple PSDU data rates within each frequency band, employing a concatenation of outer forward error correction coding (FEC), interleaving and spreading. For all frequency bands, spreading is supported by direct sequence spread spectrum (DSSS) applying various spreading factors. For the frequency bands 915 MHz and 2450 MHz, the MR-O-QPSK PHY supports a co-alternative spreading mode during the PSDU part, called multiplexed direct sequence spread spectrum (MDSSS). For the frequency bands 915 MHz and 2450 MHz, a compliant device shall support at least one of the spreading modes. The selection of SpreadingMode (either "DSSS" or "MDSSS") is obtained by a dedicated SFD value of the SHR (see 6.3.2).

During SHR and PHR, no FEC is applied but the spreading factor is considerably larger than the spreading factor during the PSDU part.

For the frequency bands 780 MHz, 915 MHz and 2450 MHz, the MR-O-QPSK PHY supports communication with legacy devices according to the specification of sections 6.8, 6.10 and 6.5, respectively, as described in subclause 6.12c.5.

Modulation is raised cosine shaped quadrature phase-shift keying (O-QPSK).

At least one of the defined frequency bands shall be implemented when supporting SUN applications.

6.12c.1 SHR and PHR spreading

For the (SHR,PHR) part of the PPDU, (N,1)-DSSS in conjunction with differential encoding shall be applied independent of the spreading mode during the PSDU part (*SpreadingMode* is either "DSSS" or "MDSSS"). Table 75k shows the spreading parameters of (N,1)-DSSS bit-to-symbol mapping, as described in 6.12c.4.4.

Table 75k— SHR,PHR parameters

Frequency band (MHz)	Chip Rate (kchip/s)	Differential Encoding	Spreading	(SHR,PHR) duration [us]
779–787	1000	yes	(64,1)-DSSS	5632
868–870	125	yes	$(16,1)_0$-DSSS	7168
902–928	1000	yes	(64,1)-DSSS	5632
2400–2483.5	2000	yes	(128,1)-DSSS	5632

6.12c.2 PSDU data rates for DSSS

The supported PSDU parameters for *SpreadingMode* "DSSS" are shown in Table 75l.

6.12c.3 PSDU data rates for MDSSS

The supported PSDU parameters for *SpreadingMode* "MDSSS" are shown in Table 75m.

6.12c.4 Modulation and coding

During the PSDU part, the MR-O-QPSK PHY shall employ forward error correction coding (FEC), interleaving and spreading of variable spreading factors. The spreading mode is either "DSSS" (for all frequency bands) or co-alternatively, "MDSSS" (for the 915 MHz and 2450 MHz frequency band).

Table 75l— PSDU parameters for *SpreadingMode* “DSSS”

Frequency band (MHz)	Chip rate (kchip/s)	RateMode	Differential Encoding	Spreading	1/2 rateFEC + interleaving	data rate (kbps)
779–787	1000	0	yes	$(16,1)_{0/1}$-DSSS	yes	31.25
		1	no	(16,4)-DSSS	yes	125
		2	no	(8,4)-DSSS	yes	250
		3	no	none	yes	500
868–870	125	0	yes	(4,1)-DSSS	yes	15.625
		1	no	none	yes	62.5
		2/3	not supported			
902–928	1000	0	yes	$(16,1)_{0/1}$-DSSS	yes	31.25
		1	no	(16,4)-DSSS	yes	125
		2	no	(8,4)-DSSS	yes	250
		3	no	none	yes	500
2400–2483.5	2000	0	yes	$(32,1)_{0/1}$-DSSS	yes	31.25
		1	no	(32,4)-DSSS	yes	125
		2	no	(16,4)-DSSS	yes	250
		3	no	(8,4)-DSSS	yes	500

Table 75m—PSDU parameters for *SpreadingMode* “MDSSS”

Frequency band (MHz)	Chip rate (kchip/s)	RateMode	Differential Encoding	Spreading	1/2 rateFEC + interleaving	data rate (kbps)
779–787	not supported					
868–870						
902–928	1000	0	no	(64,8)-MDSSS	yes	62.5
		1	no	(32,8)-MDSSS	yes	125
		2	no	(32,8)-MDSSS	no	250
		3	no	(16,8)-MDSSS	no	500
2400–2483.5	2000	0	no	(128,8)-MDSSS	yes	62.5
		1	no	(64,8)-MDSSS	yes	125
		2	no	(64,8)-MDSSS	no	250
		3	no	(32,8)-MDSSS	no	500

6.12c.4.1 Reference modulator diagram for DSSS

Figure 65k shows the reference modulator diagram when DSSS is applied during the PSDU (*SpreadingMode* is “DSSS”).

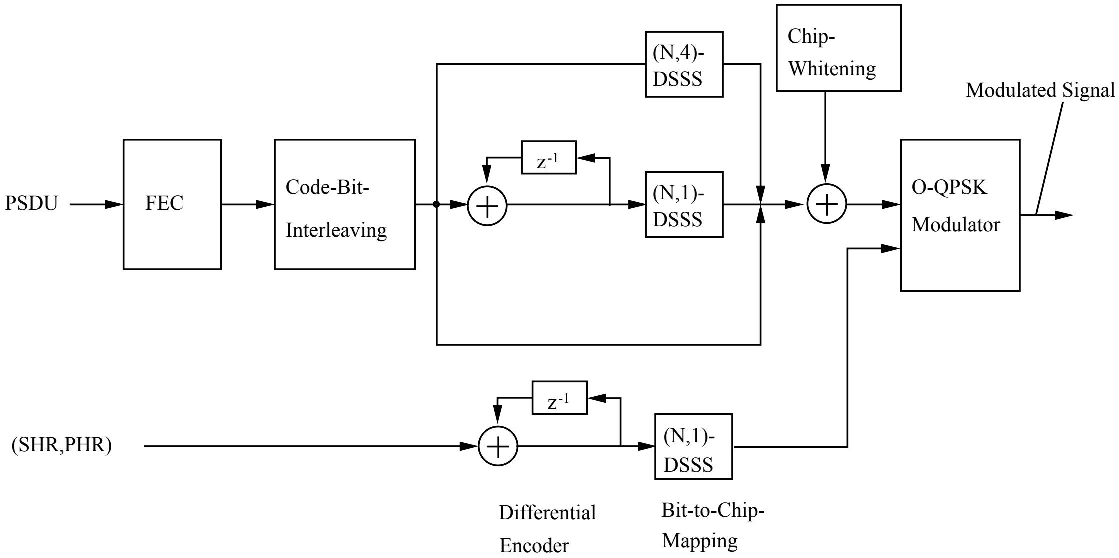


Figure 65k— Coding, interleaving, DSSS and modulation

Each bit in the (SHR,PHR) shall be processed in octet-wise order, beginning with the Preamble field and ending with the last octet of the PHR. Within each octet, the LSB, b_0, is processed first and the MSB, b_7, is processed last. The bits of the SHR and PHR shall be differentially encoded (see 6.12c.4.3) and in addition (*N*,1)-DSSS bit-to-chip mapping shall be applied as described in 6.12c.4.4.

Each bit in the PSDU shall be processed in octet-wise order, beginning with the first octet and ending with the last octet of the PSDU. Within each octet, the LSB, b_0, is processed first and the MSB, b_7, is processed last. The bits of the PSDU shall be first processed by forward error correction coding (FEC) as described in 6.12c.4.8, delivering a sequence of code-bits. The code-bits shall be interleaved as described in 6.12c.4.9. Depending on the frequency band and *RateMode*, spreading by DSSS shall be applied.

The first DSSS method applies differentially encoding of the interleaved code-bits (see 6.12c.4.3) and subsequently (*N*,1)-bit-to-chip mapping as described in 6.12c.4.4.

The second DSSS method applies (*N*,4)-bit-to-chip mapping of the interleaved code-bits as described in 6.12c.4.4.

Depending on the frequency band and *RateMode*, the output sequences of the bit-to-chip mapper shall be whitened, as shown in subclause 6.12c.4.6.

The chip sequences are modulated onto the carrier using O-QPSK modulation, as described in 6.12c.4.7.

6.12c.4.2 Reference modulator diagram for MDSSS

Figure 65l shows the reference modulator diagram when MDSSS is applied during the PSDU (*SpreadingMode* is “MDSSS”).

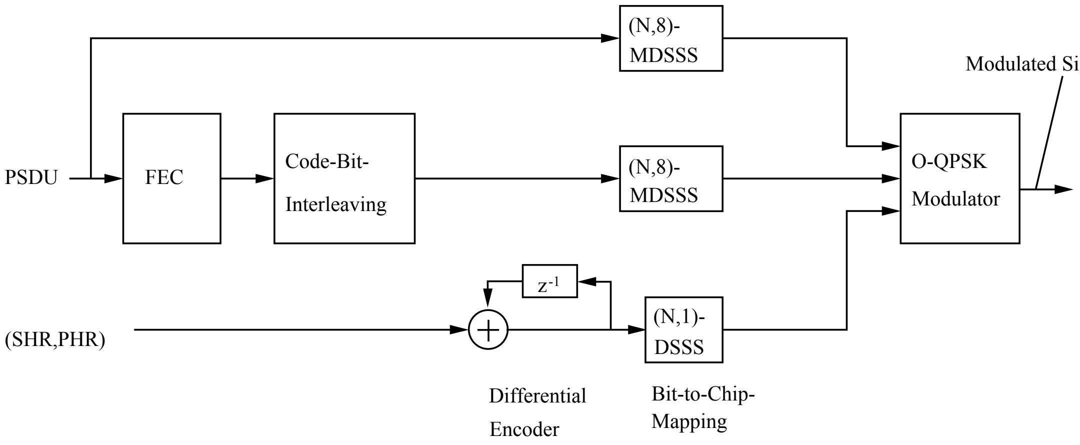


Figure 65l— Coding, interleaving, MDSSS and modulation

Each bit in the (SHR,PHR) shall be processed in octet-wise order, beginning with the Preamble field and ending with the last octet of the PHR. Within each octet, the LSB, b_0, is processed first and the MSB, b_7, is processed last. The bits of the SHR and PHR shall be differentially encoded (see 6.12c.4.3) and in addition (*N*,1)-DSSS bit-to-chip mapping shall be applied as described in 6.12c.4.4.

Each bit in the PSDU shall be processed in octet-wise order, beginning with the first octet and ending with the last octet of the PSDU. Within each octet, the LSB, b_0, is processed first and the MSB, b_7, is processed last.

Depending on *RateMode,* (see Table 75m)*,* the bits of the PSDU shall be first processed by forward error correction coding (FEC) as described in 6.12c.4.8, delivering a sequence of code-bits. When FEC is employed, the code-bits shall be interleaved as described in 6.12c.4.9, otherwise the interleaver is bypassed.

Depending on *RateMode*, (*N*,8)-MDSSS of different spreading factors shall be applied*,* see Table 75m and subclause 6.12c.4.5.

The chip sequences are modulated onto the carrier using O-QPSK modulation, as described in 6.12c.4.7.

6.12c.4.3 Differential encoding

Differential encoding is the modulo-2 addition (addition over GF(2)) of a raw bit with the previous encoded bit. This is performed by the transmitter and can be described by Equation (11):

$$E_n = R_n \oplus E_{n-1} \tag{11}$$

where

R_n is the raw bit being encoded

E_n is the corresponding differentially encoded bit

E_{n-1} is the previous differentially encoded bit

For each packet transmitted, R_0 is the first raw data bit to be encoded and E_{-1} is assumed to be zero.

If differential encoding is enabled during the PSDU part depending on the frequency band and *RateMode* (see Table 75l), it shall be continuously applied to the bits of the SHR, PHR and to the sequence of code bits at the output of the interleaver, see Figure 65m and subclauses 6.12c.4.8 and 6.12c.4.9.

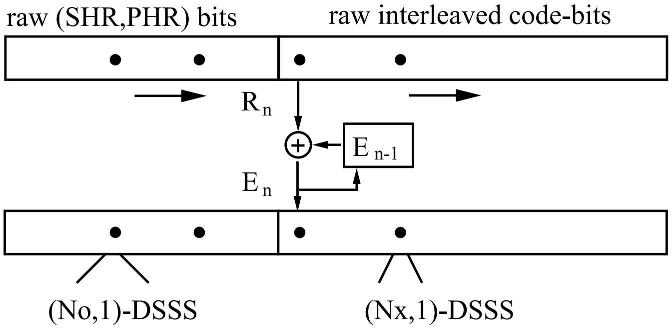


Figure 65m—Differential encoding during (SHR,PHR) and PSDU

If differential encoding is not enabled during the PSDU part depending on the frequency band and *RateMode* (see Table 75l and Table 75m), it shall be applied to the bits of the SHR and PHR only. In this case, the sequence of code-bits at the output of the interleaver (FEC is enabled) or the raw PSDU bits (FEC is not enabled) are appended to the sequences of differentially encoded bits of the (SHR,PHR) (see Figure 65n).

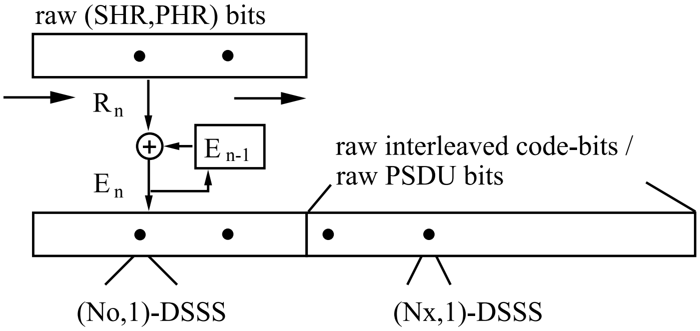


Figure 65n—Differential encoding during (SHR,PHR) only

6.12c.4.4 DSSS bit-to-chip mapping

(*N*,1)-DSSS

For (*N*,1)-DSSS, a single bit is mapped to a sequences of *N* binary valued chips: $\{0, 1\}^1 \rightarrow \{0, 1\}^N$. The number *N* of chips depends on the frequency band and *RateMode*, see Table 75l. This mapping defines a binary (*N*, *k*) block code with $k = 1$.

Table 75n through Table 75r show (*N*,1)-DSSS used in the MR-O-QPSK PHY. For $N = 1$, the chip value is equal to the input bit value (no spreading).

Note that for $N > 1$, (*N*,1)-DSSS is always preceded by differential encoding, supporting non-coherent detection of the interleaved code-bits, see Table 75k and Table 75l. For $N = 1$ (no spreading), coherent detection is required, employing a phase control loop based on the received chip samples.

Table 75n— (4,1)-DSSS bit-to-chip mapping

Input bit	Chip values (c_0 c_1 … c_3)
0	1010
1	0101

Table 75o— $(16,1)_k$-DSSS bit-to-chip mapping

k	Input bit	Chip values (c_0 c_1 … c_{15})
0	0	0010_0011_1101_0110
	1	1101_1100_0010_1001
1	0	0100_0111_1010_1100
	1	1011_1000_0101_0011

Table 75p— $(32,1)_k$-DSSS bit-to-chip mapping

k	Input bit	Chip values (c_0 c_1 … c_{31})
0	0	1101_1110_1010_0010_0111_0000_0110_0101
	1	0010_0001_0101_1101_1000_1111_1001_1010
1	0	1110_1111_0101_0001_0011_1000_0011_0010
	1	0001_0000_1010_1110_1100_0111_1100_1101

Table 75q— (64,1)-DSSS bit-to-chip mapping

Input bit	Chip values (c_0 c_1 … c_{63})
0	1011_0010_0010_0101_1011_0001_1101_0000_ _1101_0111_0011_1101_1111_0000_0010_1010
1	0100_1101_1101_1010_0100_1110_0010_1111_ _0010_1000_1100_0010_0000_1111_1101_0101

For $N = 16$, two spreading codes are defined, denoted as $(16,1)_0$-DSSS and $(16,1)_1$-DSSS, respectively. Similarly, for $N = 32$, two spreading codes are defined, denoted as denoted as $(32,1)_0$-DSSS and $(32,1)_1$-DSSS, respectively. When used during the (SHR,PHR), only $(16,1)_0$-DSSS is applied, see Table 75k. When used during the PSDU, the two spreading codes are applied in an alternating fashion, denoted as $(16,1)_{0/1}$-DSSS (see Table 75l). Similarly, for $N = 32$, the two alternating spreading codes are denoted as $(32,1)_{0/1}$-DSSS (see Table 75l). The time variance of the spreading code during the PSDU part improves spectral properties while preserving a robust and simple mechanism for carrier sense[2]. In particular, let $E_n = R_n \oplus E_{n-1}$ be the bit value at the output of the differential encoder (see Equation (11)) where R_n refers to the first code-bit at the output of the interleaver. For $k = 0, 1, \ldots$, the bits E_{n+2k} shall be spread with $(N,1)_0$-DSSS and the bits E_{n+2k+1} shall be spread with $(N,1)_1$-DSSS.

Table 75r— (128,1)-DSSS bit-to-chip mapping

Input bit	Chip values (c_0 c_1 … c_{127})
0	1001_1000_1000_1011_0100_1110_0100_0010_ _0101_0010_0110_1101_1100_0111_1010_0000_ _1101_0100_0110_0101_1101_1000_0111_0101_ _1110_0111_1101_1111_1000_0000_1010_1011
1	0110_0111_0111_0100_1011_0001_1011_1101_ _1010_1101_1001_0010_0011_1000_0101_1111_ _0010_1011_1001_1010_0010_0111_1000_1010_ _0001_1000_0010_0000_0111_1111_0101_0100

In order to exploit the capabilities of a trellis-based decoder for the outer forward error correction code (see 6.12c.4.8), it is recommended to compute a soft decision value of the detected information bits.

(*N*,4)-DSSS

When applying (*N*,4)-DSSS, a 4-tuple of bits is mapped to a sequence of *N* binary valued chips: $\{0, 1\}^4 \rightarrow \{0, 1\}^N$. This mapping defines a binary (*N*, *k*) block code with $k = 4$.

Table 75s through Table 75u show (*N*,4)-DSSS supported by the MR-O-QPSK PHY.

Table 75s— (8,4)-DSSS bit-to-chip mapping

Input bits (b_0 b_1 b_2b_3)	Chip values (c_0 c_1 … c_7)
0000	0000_0001
1000	1101_0000
0100	0110_1000
1100	1011_1001
0010	1110_0101
1010	0011_0100

---

[2] When applying chip whitening according to subclause 6.12c.4.6, the spectral properties can be improved as well but carrier sense is difficult to achieve. Since the signal-to-noise ratio (SNR) is low for modes applying (16,1)-DSSS or (32,1)-DSSS, a mechanism for carrier sense is beneficial for clear channel assessment (CCA). For the modes where chip whitening is applied (see 6.12c.4.6), the SNR is larger implying that CCA based on energy-detect may suffice.

Table 75s— (8,4)-DSSS bit-to-chip mapping

0110	1000_1100
1110	0101_1101
0001	1010_0010
1001	0111_0011
0101	1100_1011
1101	0001_1010
0011	0100_0110
1011	1001_0111
0111	0010_1111
1111	1111_1110

Table 75t— (16,4)-DSSS bit-to-chip mapping

Input bits (b_0 b_1 b_2b_3)	Chip values (c_0 c_1 … c_{15})
0000	0011_1110_0010_0101
1000	0100_1111_1000_1001
0100	0101_0011_1110_0010
1100	1001_0100_1111_1000
0010	0010_0101_0011_1110
1010	1000_1001_0100_1111
0110	1110_0010_0101_0011
1110	1111_1000_1001_0100
0001	0110_1011_0111_0000
1001	0001_1010_1101_1100
0101	0000_0110_1011_0111
1101	1100_0001_1010_1101
0011	0111_0000_0110_1011
1011	1101_1100_0001_1010
0111	1011_0111_0000_0110
1111	1010_1101_1100_0001

For (*N*,4)-DSSS, coherent detection is recommended, employing a phase control loop based on the maximum likelihood decision of the optimal codeword with respect to the (*N*,4) block code. In order to exploit the capabilities of a trellis-based decoder for the outer forward error correction code (see 6.12c.4.8), it is recommended to compute a soft decision value of each individual bit of the 4-tuple of information bits[3].

Table 75u— (32,4)-DSSS bit-to-chip mapping

Input bits (b_0 b_1 $b_2 b_3$)	Chip values (c_0 c_1 … c_{31})
0000	1101_1001_1100_0011_0101_0010_0010_1110
1000	1110_1101_1001_1100_0011_0101_0010_0010
0100	0010_1110_1101_1001_1100_0011_0101_0010
1100	0010_0010_1110_1101_1001_1100_0011_0101
0010	0101_0010_0010_1110_1101_1001_1100_0011
1010	0011_0101_0010_0010_1110_1101_1001_1100
0110	1100_0011_0101_0010_0010_1110_1101_1001
1110	1001_1100_0011_0101_0010_0010_1110_1101
0001	1000_1100_1001_0110_0000_0111_0111_1011
1001	1011_1000_1100_1001_0110_0000_0111_0111
0101	0111_1011_1000_1100_1001_0110_0000_0111
1101	0111_0111_1011_1000_1100_1001_0110_0000
0011	0000_0111_0111_1011_1000_1100_1001_0110
1011	0110_0000_0111_0111_1011_1000_1100_1001
0111	1001_0110_0000_0111_0111_1011_1000_1100
1111	1100_1001_0110_0000_0111_0111_1011_1000

For each codeword $(c_0, \ldots, c_{N-1})$, the first component, c_0, shall be transmitted first in time, and the last component, c_{N-1}, shall be transmitted last in time.

6.12c.4.5 MDSSS bit-to-chip mapping

The functional block diagram in Figure 65o is provided as a reference for specifying the Multiplexed Direct Sequence Spread Spectrum (MDSSS). Each bit in the PSDU shall be processed through the Turbo Product Code (TPC) encoding and multiplexing module. As for the horizontal code of TPC, 3 bits are encoded into *n* bits with the (*n*, 3) Hadamard code. The (4, 3) odd parity code is employed as the vertical code of TPC.

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[3] Since a binary (*N*,4) block code consists of 16 codewords only, even a brute force estimate of the a posteriori probability (or some equivalent metric) of each information bit is feasible at low implementation cost.

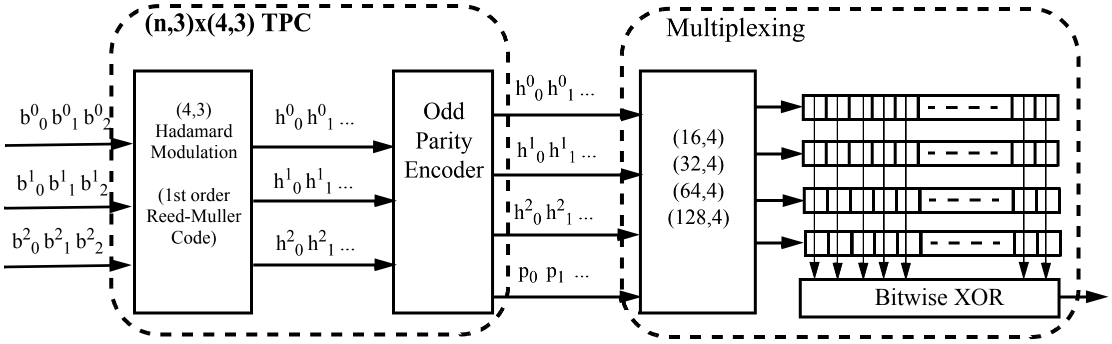


Figure 65o— MDSSS signal flow

Each octet of the PSDU shall be mapped into three horizontal input rows as specified in Table 75v. The 3 LSBs (b_0, b_1, b_2) of each octet shall map into the first horizontal input row ($b^0{}_0$, $b^0{}_1$, $b^0{}_2$), and the next 3 bits (b_3, b_4, b_5) of each octet shall map into the second horizontal input row ($b^1{}_0$, $b^1{}_1$, $b^1{}_2$). The last horizontal input row ($b^2{}_0$, $b^2{}_1$, $b^2{}_2$) shall be mapped with the last 2 bits (b_6, b_7) of each octet and the single parity bit of the octet provided with Equation (12).

$$p = b^0{}_0 \oplus b^1{}_0 \oplus b^2{}_0 \oplus b^0{}_1 \oplus b^1{}_1 \oplus b^2{}_1 \oplus b^0{}_2 \oplus b^1{}_2 \qquad (12)$$

.

Table 75v— PSDU bit stream to horizontal code input mapping

Horizontal code input	$b^0{}_0$	$b^0{}_1$	$b^0{}_2$	$b^1{}_0$	$b^1{}_1$	$b^1{}_2$	$b^2{}_0$	$b^2{}_1$	$b^2{}_2$
PSDU bit stream	Bits:0	1	2	3	4	5	6	7	p

For the horizontal coding of TPC, the three parallel 3-bit streams ($b^x{}_0$, $b^x{}_1$, $b^x{}_2$: x=0, 1, 2) are converted to the three parallel n-bit streams ($h^x{}_0$, $h^x{}_1$, $h^x{}_2$, $h^x{}_3$, ..., $h^x{}_{n-1}$) through the (n, 3) Hadamard modulator. A (n, 3) Hadamard modulation code set of the eight codewords is obtained from the first four rows of ((n/2) x (n/2)) Hadamard matrix by augmenting it with the negative of each signal. The first four rows of (n x n) Hadamard matrix are equivalent to that of (n / 4) times repeated (4 x 4) Hadamard matrix. The (4x4) Hadamard matrix, H_2, is described by Equation (13). So, the (n, 3) Hadamard modulation codes are equivalent to that of n/4 times repeated (4, 3) codes described Table 75w.

$$H_2 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \qquad (13)$$

.

Table 75w— Symbol-to-chip mapping for (4,3) Hadamard modulation

Data symbol (decimal)	Data symbol (b^x_0, b^x_1, b^x_2)	Modulator output (h^x_0, h^x_1, h^x_2, h^x_3)
0	0 0 0	1 1 1 1
1	0 0 1	1 -1 1 -1
2	0 1 0	-1 -1 1 1
3	0 1 1	-1 1 1 -1
4	1 0 0	1 -1 -1 1
5	1 0 1	1 1 -1 -1
6	1 1 0	-1 1 -1 1
7	1 1 1	-1 -1 -1 -1

As the minimum Hamming distance of (n x n) Hadamard matrix is (n/2), the minimum distance of (16,3), (32,3), (64,3), and (128,3) Hadamard modulation codes is 8, 16, 32, and 64, respectively.

For the vertical coding of TPC, the odd parity encoder converts the three parallel 4-bit streams to four parallel 4-bit streams as specified in Equation (14), where the odd parity bit is specified in Equation (15).

$$T_{unit} = \begin{bmatrix} h^0{}_0 & h^0{}_1 & h^0{}_2 & h^0{}_3 \\ h^1{}_0 & h^1{}_1 & h^1{}_2 & h^1{}_3 \\ h^2{}_0 & h^2{}_1 & h^2{}_2 & h^2{}_3 \\ p_0 & p_1 & p_2 & p_3 \end{bmatrix} \tag{14}$$

$$\begin{aligned} p_0 &= h^0{}_0 \oplus h^1{}_0 \oplus h^2{}_0 \\ p_1 &= h^0{}_1 \oplus h^1{}_1 \oplus h^2{}_1 \\ p_2 &= h^0{}_2 \oplus h^1{}_2 \oplus h^2{}_2 \\ p_3 &= h^0{}_3 \oplus h^1{}_3 \oplus h^2{}_3 \end{aligned} \tag{15}$$

As a result of (4,3) horizontal and (4,3) vertical coding with a parity bit per byte, the PSDU bit stream is transformed into a (4,3)x(4,3) TPC code block, forming (4x4) 2-dimensional data, as shown in Figure 65p.

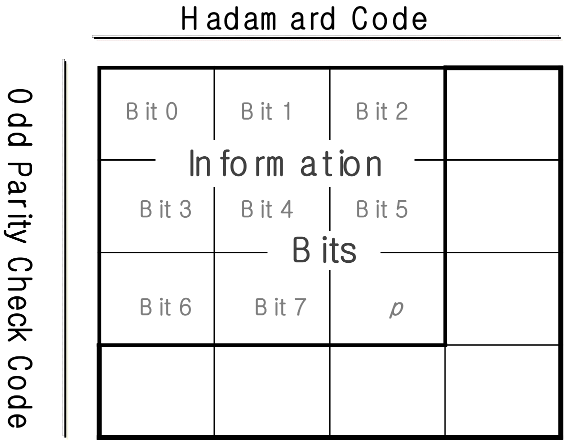


Figure 65p— Structure of turbo product codeword

The TPC encoded (4x4) bit matrix, T_{unit}, is the unit matrix for (16,8), (32,8), (64,8), and (128,8) MDSSS of Table 75m. The (16,3) Hadamard modulation output for (16, 8) MDSSS is specified in Equation (16). Similarly, the (32,3), (64,3), and (128,3) Hadamard modulation output for (32, 8), (64,8), and (128,8) MDSSS are specified in Equation (17), Equation (18), and Equation (19), respectively.

$$T_{(4\times16)} = \underbrace{\left[T_{unit}\ T_{unit}\ T_{unit}\ T_{unit}\right]}_{4} \tag{16}$$

$$T_{(4\times32)} = \underbrace{\left[T_{unit}\ T_{unit}\ T_{unit}\ T_{unit}\ T_{unit}\ T_{unit}\ T_{unit}\ T_{unit}\right]}_{8} \tag{17}$$

$$T_{(4\times64)} = \underbrace{\left[T_{unit}\ T_{unit}\ T_{unit}\ \ldots\ T_{unit}\ T_{unit}\ T_{unit}\right]}_{16} \tag{18}$$

$$T_{(4\times128)} = \underbrace{\left[T_{unit}\ T_{unit}\ T_{unit}\ \ldots\ T_{unit}\ T_{unit}\ T_{unit}\right]}_{32} \tag{19}$$

The TPC encoded output shall be transformed to the chip sequence by multiplexing four parallel bit streams vertically. As for the multiplexing code for (n, 3) MDSSS, H_2 matrix is expanded by adding the each row ($\log_2 n$)-times. To multiplex (4x16) TPC encoded output into (1x16) MDSSS chip sequence, (4x16) multiplexing code, $H_{m(4x16)}$ of Equation (20), is bitwise XOR-ed as specified in Equation (21).

$$H_{m(4\times 16)} = \begin{bmatrix} 1\ 1\ 1\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1\ 1\ 1\ 1 & -1 & -1 & -1 & -1 & 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1\ 1\ 1\ 1 & 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 \\ 1\ 1\ 1\ 1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 1 & 1 & 1 & 1 \end{bmatrix} \quad (20)$$

$$\begin{aligned} X &= T_{(4\times 16)} \oplus H_{m(4\times 16)} \\ &= \begin{bmatrix} h^0{}_0\ h^0{}_1\ h^0{}_2\ h^0{}_3 & h^0{}_0 & h^0{}_1 & h^0{}_2 & h^0{}_3 & h^0{}_0 & h^0{}_1 & h^0{}_2 & h^0{}_3 & h^0{}_0 & h^0{}_1 & h^0{}_2 & h^0{}_3 \\ h^1{}_0\ h^1{}_1\ h^1{}_2\ h^1{}_3 & -h^1{}_0 & -h^1{}_1 & -h^1{}_2 & -h^1{}_3 & h^1{}_0 & h^1{}_1 & h^1{}_2 & h^1{}_3 & -h^1{}_0 & -h^1{}_1 & -h^1{}_2 & -h^1{}_3 \\ h^2{}_0\ h^2{}_1\ h^2{}_2\ h^2{}_3 & h^2{}_0 & h^2{}_1 & h^2{}_2 & h^2{}_3 & -h^2{}_0 & -h^2{}_1 & -h^2{}_2 & -h^2{}_3 & -h^2{}_0 & -h^2{}_1 & -h^2{}_2 & -h^2{}_3 \\ p_0\ p_1\ p_2\ p_3 & -p_0 & -p_1 & -p_2 & -p_3 & -p_0 & -p_1 & -p_2 & -p_3 & p_0 & p_1 & p_2 & p_3 \end{bmatrix} \end{aligned} \quad (21)$$

Similarly, The TPC encoded (4x32), (4x64), and (4x128) bit matrix shall be multiplexed into the (1,32), (1,64), and (1,128) output chip sequence with the (4x32), (4x64), and (4x128) multiplexing code as specified in Equation (22).

$$\begin{aligned} X &= T \oplus H_m \\ &= \begin{cases} \left[T_{(4\times 16)} \oplus H_{m(4\times 16)}\right] & ,n = 16 \\ \left[T_{(4\times 16)} \oplus H_{m(4\times 16)}\ T_{(4\times 16)} \oplus H_{m(4\times 16)}\right] & ,n = 32 \\ \left[T_{(4\times 16)} \oplus H_{m(4\times 16)}\ T_{(4\times 16)} \oplus H_{m(4\times 16)}\ T_{(4\times 16)} \oplus H_{m(4\times 16)}\right] & ,n = 64 \\ \left[T_{(4\times 16)} \oplus H_{m(4\times 16)}\ T_{(4\times 16)} \oplus H_{m(4\times 16)}\ T_{(4\times 16)} \oplus H_{m(4\times 16)}\ T_{(4\times 16)} \oplus H_{m(4\times 16)}\right] & ,n = 128 \end{cases} \\ &= \left[\bar{c}_0\ \bar{c}_1\ \bar{c}_2\ \bar{c}_3\ \bar{c}_4\ \ldots\ \bar{c}_{i+j}\right]\ ,(0 \le i \le 31,\ \ 0 \le j < (n \div 16)) \end{aligned} \quad (22)$$

The multiplexed output bit stream shall be bitwise XOR-ed by the covering code for the chip and symbol synchronization. For each of (16,8), (32,8), (64,8), (128,8) MDSSS, covering code shall be bit 0 of $(16,1)_0$-DSSS, $(32,1)_0$-DSSS, (64,1)-DSSS, (128,1)-DSSS code, which are described in Table 75o, Table 75p, Table 75q, and Table 75r, respectively.

Then, the final output chip sequence of length (n,8) MDSSS shall be described in Equation (23).

$$c_{i+j} = \overline{c_i} \oplus m_{i+j}, (0 \le i \le 31, \quad 0 \le j < (n \div 16))$$

where

$$\begin{aligned}
\overline{c_0} &= (h^0{}_0) + (h^1{}_0) + (h^2{}_0) + (p_0) \\
\overline{c_1} &= (h^0{}_1) + (h^1{}_1) + (h^2{}_1) + (p_1) \\
\overline{c_2} &= (h^0{}_2) + (h^1{}_2) + (h^2{}_2) + (p_2) \\
\overline{c_3} &= (h^0{}_3) + (h^1{}_3) + (h^2{}_2) + (p_3) \\
\overline{c_4} &= (h^0{}_0) + (-h^1{}_0) + (h^2{}_0) + (-p_0) \\
\overline{c_5} &= (h^0{}_1) + (-h^1{}_1) + (h^2{}_1) + (-p_1) \\
\overline{c_6} &= (h^0{}_2) + (-h^1{}_2) + (h^2{}_2) + (-p_2) \\
\overline{c_7} &= (h^0{}_3) + (-h^1{}_3) + (h^2{}_2) + (-p_3) \\
\overline{c_8} &= (h^0{}_0) + (h^1{}_0) + (-h^2{}_0) + (-p_0) \\
\overline{c_9} &= (h^0{}_1) + (h^1{}_1) + (-h^2{}_1) + (-p_1) \\
\overline{c_{10}} &= (h^0{}_2) + (h^1{}_2) + (-h^2{}_2) + (-p_2) \\
\overline{c_{11}} &= (h^0{}_3) + (h^1{}_3) + (-h^2{}_2) + (-p_3) \\
\overline{c_{12}} &= (h^0{}_0) + (-h^1{}_0) + (-h^2{}_0) + (p_0) \\
\overline{c_{13}} &= (h^0{}_1) + (-h^1{}_1) + (-h^2{}_1) + (p_1) \\
\overline{c_{14}} &= (h^0{}_2) + (-h^1{}_2) + (-h^2{}_2) + (p_2) \\
\overline{c_{15}} &= (h^0{}_3) + (-h^1{}_3) + (-h^2{}_2) + (p_3)
\end{aligned} \tag{23}$$

6.12c.4.6 Chip whitening

When *SpreadingMode* is “DSSS”, the chip sequences shall be whitened, depending on the frequency band and *RateMode* as shown in Table 75x. For all other modes, no chip whitening shall be applied.

Table 75x— Chip Whitening for “DSSS”

Frequency band (MHz)	RateMode
778–780	2,3
868–870	0,1
902–928	2,3
properties–2483.5	3

Chip whitening is the modulo-2 addition (addition over GF(2)) of a chip of the PSDU part at the output of the bit-to-chip mapper with the value of a cyclic *m*-sequence $S_{(k \bmod (2^m - 1))}$ of length $2^m - 1$ for $m = 9$. This shall be performed by the transmitter and is described by Equation (24):

$$c'_k = c_k \oplus S_{(k \bmod 511)} \tag{24}$$

where

c_k is the raw PSDU chip being whitened
c'_k is the whitened chip.

Index k starts at 0, referring to the first chip of the PSDU part at the output of the bit-to-chip mapper and is increased by one at every chip interval. Figure 65q shows the whitening process. At $k = 0$, the register shall be initialized with

$$(u_{k-1}, u_{k-1}, \ldots, u_{k-9}) = (1, 0, 0, 0, 0, 0, 0, 0, 0) \tag{25}$$

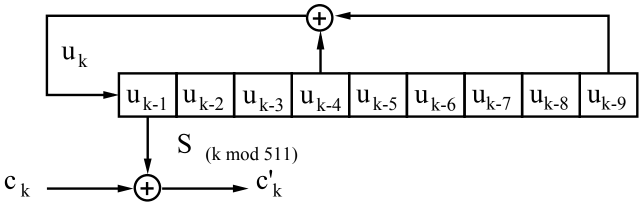


Figure 65q— Chip whitening

6.12c.4.7 Modulation parameters for O-QPSK

A chip value shall be mapped into a binary real valued symbol out of {-1,1} by the mapping

$$\zeta(c) = \begin{cases} -1, c = 0 \\ 1, c = 1 \end{cases} \tag{26}$$

The raised cosine pulse shape with roll-off factor of $r = 0.8$ is used to represent each baseband symbol and is described by

$$p(t) = \begin{cases} \dfrac{\sin(\pi t/T_c)}{\pi t/T_c} \times \dfrac{\cos(r\pi t/T_c)}{1 - 4r^2t^2/T_c^2}, t \neq 0 \\ 1, t = 0 \end{cases} \tag{27}$$

where the chip duration T_c is the inverse of the chip rate, see Table 75l and Table 75m.

Given the discrete-time sequence $\{c_k\}_0^{N_{PPDU}-1}$ of N_{PPDU} consecutive chip samples, the continuous-time pulse shaped complex baseband signal is given by

$$y(t) = \sum_{k=0}^{N_{PPDU}-1} \zeta(c_{2k})p(t - 2kT_c) + j\zeta(c_{2k+1})p(t - 2kT_c - T_c) \tag{28}$$

with ζ according to Equation (26).

6.12c.4.8 Forward error correction (FEC)

Depending on *RateMode* and *SpreadingMode*, forward error correction coding shall be employed on the PSDU bits, applying 1/2 rate convolutional coding with constraint length $K = 7$ using the generator polynomials shown in Equation (29) and Equation (30).

$$G_0(x) = 1 + x^2 + x^3 + x^5 + x^6 \tag{29}$$

$$G_1(x) = 1 + x + x^2 + x^3 + x^6 \tag{30}$$

The encoder is shown in Figure 65r where addition is over GF(2).

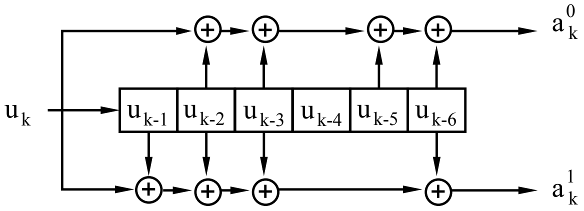


Figure 65r— Convolutional encoder

Prior to convolutional encoding, the PSDU shall be extended by appending a termination sequence of 6 zero bits and a sequence of additional bits (pad bits) as shown in Figure 65s. The pad bits shall be set to zero and the number of pads bits, N_{PAD}, is computed from the length of the PSDU in octets (LENGTH) as follows:

$$N_B = \text{ceiling}((8 \times \text{LENGTH} + 6)/(N_{\text{INTRLV}}/2)) \tag{31}$$

$$N_D = N_B \times (N_{\text{INTRLV}}/2) \tag{32}$$

$$N_{\text{PAD}} = N_D - (8 \times \text{LENGTH} + 6) \tag{33}$$

The number of code-bits referring to a single interleaving block, N_{INTRLV}, is defined in subclause 6.12c.4.9. The function ceiling (.) is a function that returns the smallest integer value greater than or equal to its argument value.

PSDU	000000	pad bits

Figure 65s— PSDU extension prior to encoding

The output sequence of code-bits *z* shall be generated according to Equation (34):

$$z = \{\ldots\ a_k^0, a_k^1, a_{k+1}^0, a_{k+1}^1, a_{k+2}^0, a_{k+2}^1\ \ldots\} = \{z_0, z_1, \ldots, z_{2N_D-1}\} \tag{34}$$

i. e., a_k^0 is preceding sample a_k^1.The first sample, z_0, shall be passed to the interleaver first in time, and the last sample, z_{2N_D-1}, shall be passed to the interleaver last in time.

6.12c.4.9 Code-bit interleaving

Interleaving of code-bits shall be employed in conjunction with FEC in order to improve robustness against burst errors and to break correlation of consecutive bits when applying (*N*,4) or (*N*,8) bit-to-chip mapping. No interleaving shall be employed if FEC is not used, see Table 75m.

The sequence of code-bits, *z*, consists of N_B subsequences

$$z^j = \{z_{jN_{\mathrm{INTRLV}}}, \ldots, z_{((j+1)N_{\mathrm{INTRLV}}-1)}\} = \{z^j_0, \ldots, z^j_{N_{\mathrm{INTRLV}}-1}\} \quad j = 0, \ldots, N_B - 1$$

of length N_{INTRLV}, with N_B described in Equation (31) and N_{INTRLV} shown in Table 75y.

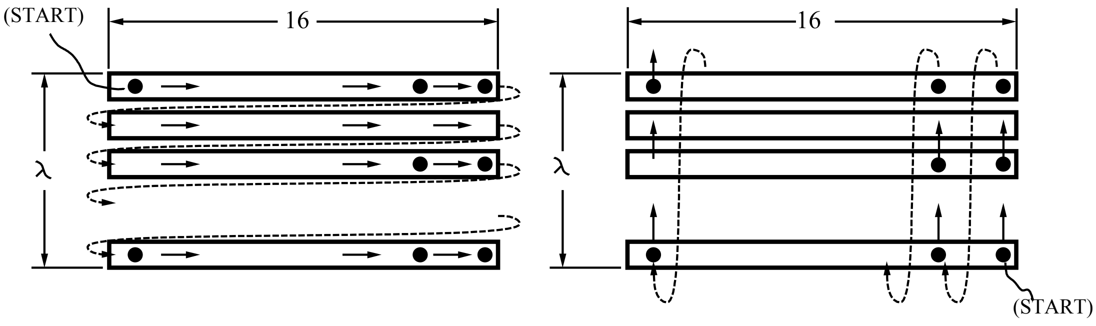
The interleaver is defined by a permutation. The index of the code-bits before the permutation shall be denoted by *k,* where $k = 0$ refers to the first sample, z^j_0, and $k = N_{\mathrm{INTRLV}} - 1$ refers to the last sample, $z^j_{N_{\mathrm{INTRLV}}-1}$, passed to the interleaver for a given subsequence z^j. The index *i* shall be the index after the permutation. The permutation is defined by the rule

$$i = \frac{N_{\mathrm{INTRLV}}}{\lambda}((N_{\mathrm{INTRLV}} - 1 - k) \bmod \lambda) + \mathrm{floor}\left(\frac{N_{\mathrm{INTRLV}} - 1 - k}{\lambda}\right) \quad k = 0, \ldots, N_{\mathrm{INTRLV}} - 1 . \qquad (35)$$

Table 75y— Parameters of the interleaver

degree λ	**depth** N_{INTRLV}
11	$16 \times 11 = 176$

where the degree λ is given in Table 75y. The function floor (.) is a function that returns the largest integer value less than or equal to its argument value. The process of interleaving a subsequence is shown in Figure 65t. The first subsequence, z^0, shall be processed first in time and the last subsequence, z^{N_B-1}, shall be processed last in time.



FILL IN READ OUT

Figure 65t— Interleaver

The de-interleaver, which performs the inverse relation is defined by the rule

$$k = \lambda(N_{\mathrm{INTRLV}} - 1 - i) - (N_{\mathrm{INTRLV}} - 1) \times \mathrm{floor}\left(\frac{\lambda(N_{\mathrm{INTRLV}} - 1 - i)}{N_{\mathrm{INTRLV}}}\right) \quad i = 0, \ldots, N_{\mathrm{INTRLV}} - 1 \qquad (36)$$

6.12c.5 Support of legacy devices of the 780 MHz, 915 MHz and 2450 MHz O-QPSK PHY

When operating in the 779–787 MHz frequency band, a compliant device of the MR-O-QPSK PHY shall be able to communicate with devices of the 780 MHz band O-QPSK PHY within the specifications given in section 6.8.

When operating in the 902–928 MHz frequency band, a compliant device of the MR-O-QPSK PHY shall be able to communicate with devices of the 915 MHz band O-QPSK PHY within the specifications given in section 6.10.

When operating in the 2400–2483.5 MHz frequency band, a compliant device of the MR-O-QPSK PHY shall be able to communicate with devices of the 2450 MHz band O-QPSK PHY within the specifications given in section 6.5.

Legacy support is feasible at low additional implementation cost due to the following specifications of the MR-O-QPSK PHY:

- O-QPSK modulation is used. O-QPSK with half-sine shaping is very similar to O-QPSK with raised cosine shaping. Since the impulse response of a raised cosine shaping filter satisfies the first Nyquist criteria, EVM specification of 6.13.3 can be easily met.
- For operation in the 779–787 MHz or 902–928 MHz band, the chip rate is 1000 kchip/s. This simplifies sensing of legacy preambles while sensing for a preamble of the MR-O-QPSK PHY.
- For operation in the 779–787 MHz band, the center frequencies of the channels are the same as the center frequencies specified in 6.2.1.3.
- For operation in the 902–928 MHz band, the center frequencies of the channels are the same as the center frequencies specified in .
- For operation in the 779–787 MHz band, the (16,4)-DSSS code used for bit-to-chip mapping (see Table 75t) is the same as the code specified in 6.8. Transmitting a legacy signal can be achieved by bypassing FEC and interleaver and passing a legacy IEEE 802.15.4 PPDU according to 6.3 to the (16,4)-DSSS unit, see Figure 65u.
- For operation in the 902–928 MHz band, the (16,4)-DSSS code used for bit-to-chip mapping (see Table 75t) is the same as the code specified in 6.10. Transmitting a legacy signal can be achieved by bypassing FEC and interleaver and passing a legacy IEEE 802.15.4 PPDU according to 6.3 to the (16,4)-DSSS unit, see Figure 65u.
- For operation in the 2400–2483.5 MHz band, the chip rate is 2000 kchip/s. This simplifies sensing of legacy preambles while sensing for a preamble of the MR-O-QPSK PHY.
- For operation in the 2400–2483.5 MHz band, the (32,4)-DSSS code used for bit-to-chip mapping (see Table 75u) is the same as the code specified 6.5. Transmitting a legacy signal can be achieved by bypassing FEC and interleaver and passing a legacy IEEE 802.15.4 PPDU according 6.3 to the (32,4)-DSSS unit, see Figure 65u.
- For operation in the 2400–2483.5 MHz band, the center frequencies of the channels are the same as the center frequencies specified in .

6.12c.6 Radio specification

6.12c.6.1 Clock offset tolerance

The clock offset tolerance shall be less or equal to ± 20 ppm. Carrier frequency offset and symbol timing drift due to clock offset shall be locked. When communicating with legacy devices (see 6.12c.5), the receiver shall be capable to receive signals with a clock offset tolerance of less or equal to ± 40 ppm.

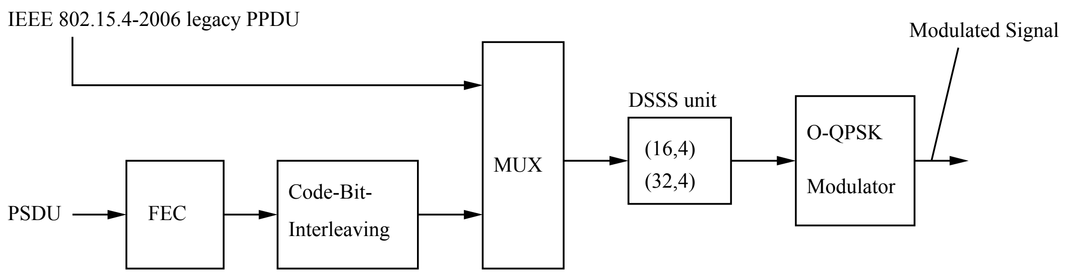


Figure 65u— Legacy support for the 780 MHz, 915 MHz and 2450 MHz O-QPSK PHY

6.12c.6.2 Receiver sensitivity

Under the conditions specified in 6.1.7, a compliant device shall be capable of achieving a sensitivity of the values given in Table 75z and Table 75aa or better.

Table 75z— Required receiver sensitivity for *SpreadingMode* “DSSS” [dBm]

Frequency band (MHz)	RateMode			
	0	1	2	3
779–787	–105	–100	–95	–90
868–870	–105	–100	not supported	
902–928	–105	–100	–95	–90
2400–2483.5	–105	–100	–95	–90

Table 75aa— Required receiver sensitivity for S*preadingMode* “MDSSS” [dBm]

Frequency band (MHz)	RateMode			
	0	1	2	3
779–787	not supported			
868–870				
902–928	–105	–100	–95	–90
2400–2483.5	–105	–100	–95	–90

6.12c.6.3 Adjacent channel rejection

The interference-to-signal ratio (ISR) is the maximum ratio of the signal power of an interferer relative to the signal power of the desired signal that leads to a frame error rate (FER) of less than 0.01. The adjacent channel rejection shall be measured as follows: the desired signal shall be an MR-O-QPSK compliant signal, of pseudo-random PSDU data. For a given *RateMode*, the desired signal is input to the receiver at a level 3 dB above the maximum allowed receiver sensitivity of Table 75z and Table 75aa.

The interfering signal shall be an MR-O-QPSK compliant signal with the following characteristics:

— pseudo-random PSDU,

— *SpreadingMode* is “DSSS”,

— the same chip rate as the desired signal,

— chip-whitening enabled.

The interferer is separated in frequency by $|\Delta f|$ from the carrier frequency of the desired channel with a minimum ISR, as shown in Table 75ab. The test shall be performed for only one interfering signal at a time. The receiver shall meet the error rate criteria defined in 6.1.7 under these conditions.

Table 75ab— Minimum interference-to-signal ratio (ISR) depending on $|\Delta f|$

frequency band (MHz) 779–787	$|\Delta f|$ (MHz)	2.0	4.0
	ISR (dB)	0	30
frequency band (MHz) 868–870	$|\Delta f|$ (MHz)	0.25	0.5
	ISR (dB)	0	20
frequency band (MHz) 902–928	$|\Delta f|$ (MHz)	2.0	4.0
	ISR (dB)	0	30
frequency band (MHz) 2400–2483.5	$|\Delta f|$ (MHz)	5.0	10.0
	ISR (dB)	0	30

6.12c.6.4 CCA specifications

The detection time T_{CCA} for clear channel assessment (CCA) is shown in Table 75ac. The ED threshold shall correspond to a received signal power of at most –90 dBm, when applying CCA Mode 1 or CCA Mode 3 (see 6.13.9).

Table 75ac— CCA duration

Frequency band (MHz)	T_{CCA} in microseconds (us)
779–787	512
868–870	1024
902–928	512
2400–2483.5	512

6.13 General radio specifications

6.13.1 TX-to-RX turnaround time

TBD

6.13.2 RX-to-TX turnaround time

Insert the following paragraph at the end of 6.13.2:

In the case of the MR-O-QPSK PHY, the RX-to-TX turnaround time is defined as the shortest time possible at the air interface from the trailing edge of the last chip sample of a received PPDU (including chip samples due to PSDU extension when FEC and interleaving is applied, as described in 6.12c.4.8) to the leading edge of the first chip sample of the next transmitted PPDU. The RX-to-TX turnaround time shall be less than or equal to *aSUNTurnaroundTime*.

6.13.3 Error-vector magnitude (EVM) definition

Change the last paragraph of 6.13.3 as indicated:

With the exception of the UWB PHY transmitter ~~as~~ described in 6.12, ~~and~~ the CSS PHY transmitter ~~as~~ described in 6.6, the MR-FSK PHY described in 6.12a, and the OFDM PHY transmitter described in 6.12b, a transmitter shall have EVM values of less than 35% when measured for 1000 chips. The error-vector measurement shall be made on baseband I and Q chips after recovery through a reference receiver system. The reference receiver shall perform carrier lock, symbol timing recovery, and amplitude adjustment while making the measurements.

6.13.4 Transmit center frequency tolerance

Change the first paragraph of 6.13.4 as indicated:

The transmitted center frequency tolerance shall be ± 40 ppm maximum, except in the cases of the MR-FSK PHY and UWB PHY. In the case of the MR-FSK PHY, the transmit frequency tolerance is given in 6.12a.5. In the case of the UWB PHY, ~~in which~~ the tolerance on the chipping clock given in 6.12.12.3 takes precedence and the center frequency tolerance is ± 20 ppm. It should be noted that a tighter frequency tolerance could facilitate a more precise range outcome for UWB devices.

6.13.5 Transmit power

6.13.6 Receiver maximum input level of desired signal

Change the first paragraph of 6.13.6 as indicated:

The receiver maximum input level is the maximum power level of the desired signal present at the input of the receiver for which the error rate criterion in 6.1.7 is met. A receiver shall have a receiver maximum input level greater than or equal to –20 dBm with the exception of a UWB receiver, which shall have a maximum input level greater than or equal to –45 dBm/MHz, and an OFDM receiver, which shall provide a maximum PER of 10% with a PSDU length of 250 bytes with a receiver maximum input level greater than or equal to -20 dBm.

6.13.7 Receiver ED

6.13.8 Link quality indicator (LQI)

6.13.9 Clear channel assessment (CCA)

Change the last paragraph of 6.13.9 as indicated:

The PHY PIB attribute *phyCCAMode* (see 6.4) shall indicate the appropriate operation mode. The CCA parameters are subject to the following criteria:

a) Except for the MR-O-QPSK PHY, the ~~The~~ ED threshold shall correspond to a received signal power of at most 10 dB above the specified receiver sensitivity (see 6.7.3.4, 6.8.3.4, 6.9.3.4, 6.10.3.4, and 6.11.3.4). For the MR-O-QPSK PHY, the ED threshold shall comply with the specification of 6.12c.6.4.

b) Except for the MR-O-QPSK PHY, the ~~The~~ CCA detection time shall be equal to 8 symbol periods for the 868/915 MHz and the 2450 MHz bands or *phyCCADuration* symbol periods for the 950 MHz band PHY. The UWB CCA detection time for CCA mode 6 shall be equal to 40 mandatory symbol periods, which includes at least 8 (multiplexed) preamble symbols (see 6.12.14). For the MR-O-QPSK PHY, the CCA detection time shall comply with the specifications of 6.12c.6.4.

6.13.9a Channel to channel slew times (per band) (max)

6.13.9b Transmit and power amplifier rise and fall times (max)

7. MAC sublayer specification

7.1 MAC sublayer service specification

7.2 MAC frame formats

7.2.1 General MAC frame format

Replace Figure 79 with the following figure:

Octets: 2	**1**	**0/2**	**0/2/8**	**0/2**	**0/2/8**	**0/5/6/10/14**	**variable**	**2/4**
Frame Control	Sequence Number	Destination PAN Identifier	Destination Address	Source PAN Identifier	Source Address	Auxiliary Security Header	Frame Payload	FCS
		Addressing fields						
MHR							MAC Payload	MFR

Figure 79—General MAC frame format

7.2.1.1 Frame Control field

7.2.1.2 Sequence Number field

7.2.1.3 Destination PAN Identifier field

7.2.1.4 Destination Address field

7.2.1.5 Source PAN Identifier field

7.2.1.6 Source Address field

7.2.1.7 Auxiliary Security Header field

7.2.1.8 Frame Payload field

7.2.1.9 FCS field

Change the first paragraph of 7.2.1.9 as indicated:

The FCS field ~~is~~ may be either 2 or 4 octets in length and contains a 16-bit ITU-T CRC or a 32-bit CRC (equivalent to ANSI X3.66-1979), respectively. The FCS is calculated over the MHR and MAC payload parts of the frame. A device compliant with the MRFSK PHY shall implement the 4-octet FCS.

Change the second paragraph of 7.2.1.9 as indicated:

The 2-octet FCS shall be calculated using the following standard generator polynomial of degree 16:

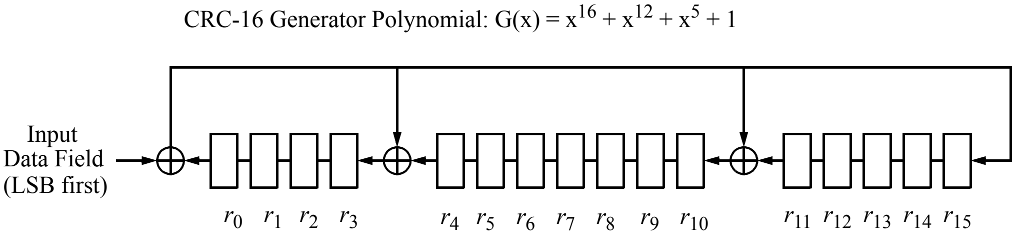
Change the third paragraph of 7.2.1.9 as indicated:

The 2-octet FCS shall be calculated for transmission using the following algorithm:

Change the sixth paragraph as indicated:

The 2-octet FCS for this case would be the following:

Replace Figure 81 as indicated:



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 81—Typical 2-octet FCS implementation

Insert the following paragraphs at the end of 7.2.1.9:

The 4-octet FCS is calculated using the following standard generator polynomial of degree 32:

$$G_{32}(x) = x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^{8} + x^{7} + x^{5} + x^{4} + x^{2} + x + 1 \qquad (37)$$

The 4-octet FCS is the one's complement of the modulo 2 sum of the two remainders in a) and b):

a) The remainder resulting from $[(xk*(x^{31}+x^{30}+...)]$ divided (modulo 2) by $G_{32}(x)$, where 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 x^{32} and then divided by $G_{32}(x)$.

At the transmitter, the initial remainder of the division shall be preset to all ones and then modified via division of the calculation field by the generator polynomial $G_{32}(x)$. The one’s complement of this remainder is the 4-octet FCS field.

At the receiver, the initial remainder shall be preset to all ones. The serial incoming bits of the calculation field and FCS, when divided by $G_{32}(x)$ in the absence of transmission errors, result in a unique non-zero remainder value. The unique remainder value is the polynomial shown in Equation (38):

$$x^{31} + x^{30} + x^{26} + x^{25} + x^{24} + x^{18} + x^{15} + x^{14} + x^{12} + x^{11} + x^{10} + x^{8} + x^{6} + x^{5} + x^{4} + x^{3} + x + 1 \quad (38)$$

7.2.2 Format of individual frame types

7.2.2.1 Beacon frame format

Replace Figure 82 with the following figure:

Octets: 2	**1**	**4/10**	**0/5/6/10/14**	**2**	**variable**	**variable**	**variable**	**2/4**
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	Superframe Specification	GTS fields (Figure 83)	Pending address fields (Figure 84)	Beacon Payload	FCS
MHR				MAC Payload				MFR

Figure 82—Beacon frame format

7.2.2.2 Data frame format

Replace Figure 90 with the following figure:

Octets: 2	**1**	**(see 7.2.2.2.1)**	**0/5/6/10/14**	**variable**	**2/4**
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	Data Payload	FCS
MHR				MAC Payload	MFR

Figure 90—Data frame format

7.2.2.3 Acknowledgment frame format

Replace Figure 91 with the following figure:

Octets: 2	**1**	**2/4**
Frame Control	Sequence Number	FCS
MHR		MFR

Figure 91—Acknowledgment frame format

7.2.2.4 MAC command frame format

Replace Figure 92 with the following figure:

Octets: 2	1	(see 7.2.3)	0/5/6/10/14	1	variable	2/4
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	Command Frame Identifier	Command Payload	FCS
MHR				MAC Payload		MFR

Figure 92—MAC command frame format

7.3 MAC command frames

Change Table 123 (the entire table is not shown) as indicated:

.

Table 123—MAC command frames

Command frame identifier	Command name	RFD		Subclause
		Tx	Rx	
0x0a	Request to join			7.3.9a
0x0b	Request to join response			7.3.9b
~~0x0a~~0x0c–0xff	Reserved			—

Change the second paragraph of 7.3 as indicated:

How the MLME shall construct the individual commands for transmission is detailed in 7.3.1 through ~~7.3.9~~7.3.9b. MAC command reception shall abide by the procedure described in 7.5.6.2.

Insert the following new subclauses following 7.3.9.2:

7.3.9a Request to join (RTJ) command

The RTJ command allows a low energy discovery mechanism to be used by a device to advertise to other devices that it wishes to and is capable of joining an existing PAN (beacon-enabled or nonbeacon-enabled). This command shall be sent by an unassociated device that wishes to discover and associate with a PAN.

The RJT command is formatted as illustrated in Figure 103a.

octets: (see 7.2.2.4)	1
MHR fields	Command Frame Identifier (see Table 123)

Figure 103a—RTJ 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 of the Frame Control field shall be set to two (i.e., 16-bit short addressing).

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 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).

7.3.9b Request to joint response (RTJR) command

The RTJR is issued by a device upon receipt of the RTJ command. The RTJR acknowledges the request and provides a capabilities payload, as defined in 7.5.8b, to the joining device, thus conveying information on the current communications attributes using the Channel Band Descriptor (CBD) index detailed in 6.4.2.x.

The RJT command is formatted as illustrated in Figure 103b.

octets: (see 7.2.2.4)	1
MHR fields	Command Frame Identifier (see Table 123)

Figure 103b—RTJ command format

The Source Addressing Mode and Destination 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. The Acknowledgment Request subfield and Security Enabled subfield shall be set to zero.

The Destination PAN Identifier field shall contain the PAN identifier assigned to the responding device if it is a PAN coordinator, or set to the broadcast PAN ID (i.e., 0xffff) if the device is not a PAN coordinator. The Destination Address field shall contain an extended address equal to the source address of the received RTJ command.

7.4 MAC constants and PIB attributes

7.4.1 MAC constants

7.4.2 MAC PIB attributes

Change Table 127 (the entire table is not shown) as indicated:

7.5 MAC functional description

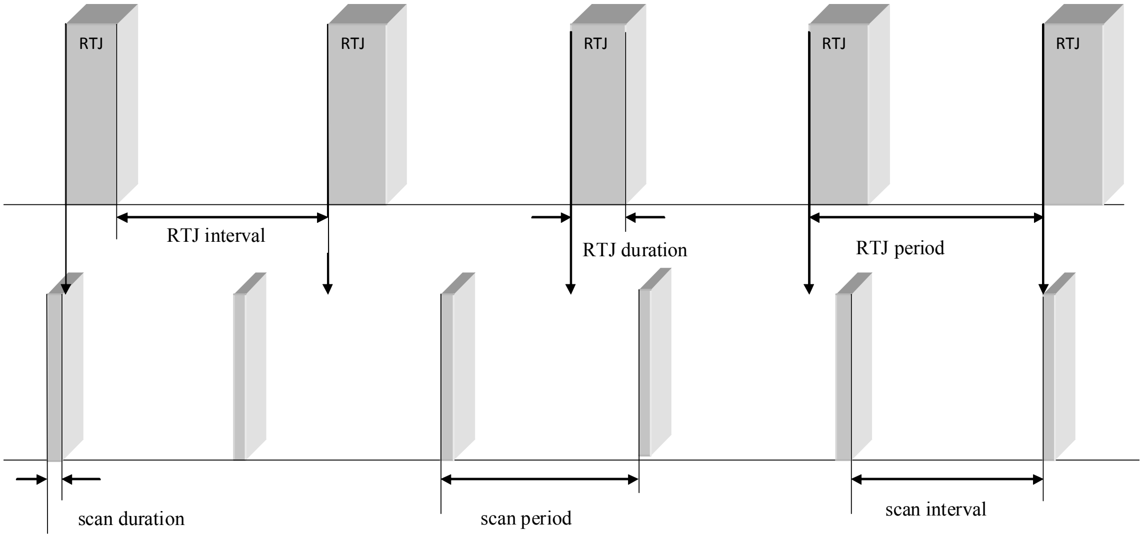
Insert the following new subclauses after 7.5.8:

Table 127—MAC PIB attributes

Attribute	Identifier	Type	Range	Description	Default
macSyncSymbolOffset†	0x5b	Integer	0x000–0x100 for the 2.4 GHz PHY 0x000–0x400 for the 868/915 MHz PHYs and the MRFSK PHYs	The offset, measured in symbols, between the symbol boundary at which the MLME captures the timestamp of each transmitted or received frame, and the onset of the first symbol past the SFD, namely, the first symbol of the Length field.	Implementation specific

7.5.8a Common signaling mode (CSM)

A single, unique CSM is established for each regulatory domain to ensure all devices within each device class share a set of common signaling attributes. All SUN devices will periodically listen for RTJ commands using the common signaling attributes defined by the CSM for the supported device class during periods of inactivity. The device will utilize the passive channel scan capability defined in 7.5.2.1.3, as extended for P802.15.4g to scan for the RTJ signals. Figure 112a provides an example that could be used to define the maximum number of scans required to capture the RTJ command. A recommended minimum duration and interval for RTJ scanning is defined in Table Q.1 in Annex Q.



(k) = Integer

scan interval = (k) beacon period

$$\text{\# of scans to converge} = \frac{\text{RTJ period}}{\text{scan duration}}$$

Example

Beacon Period mS	1000	BI+BD
Beacon Duration mS	100	
Beacon Interval mS	900	
Scan Period mS	1015	SI+SD
Scan Duration mS	15	
Scan Interval mS	1000	K*BP
k	1	
Number of scans	66.67	
Max Scan Time S	676.67	SP*nS

Average scan time = Max Scan Time /2

Figure 112a—Channel scan duration and interval

7.5.8b Capabilities message (CM)

The capabilities message utilizes the Channel Band Descriptor (CBD) index, detailed in 6.4.2.x, to communicate one or more supported set(s) of communications attributes. Following the reception of an RTJ command, an associated device will transmit an RTJR command frame with the payload consisting of CBDs using the CSM for each supported set of communications attributes starting with the CBD representing the current network communications attributes. The device attempting to join the network will set its communications attributes to match the CBD information contained in the payload of the received RTJR message that represents the current networks communications attributes. The joining device may then execute the association process, as defined in 7.5.3.1. Coordination of this type is performed by an upper layer network management entity (NME). The following text describes message structures which could be implemented by such an NME. When two devices have exchanged capabilities information, the NME may compare PHY capabilities sets and determine the mutually supported modes. Other factors, such as channel conditions, would normally be considered in selecting an optimal mode for network operation.

The following text describes message structures which could be implemented by such an NME. Figure 112b shows an example of a RTJ/RTJR packet sequence using the CSM.

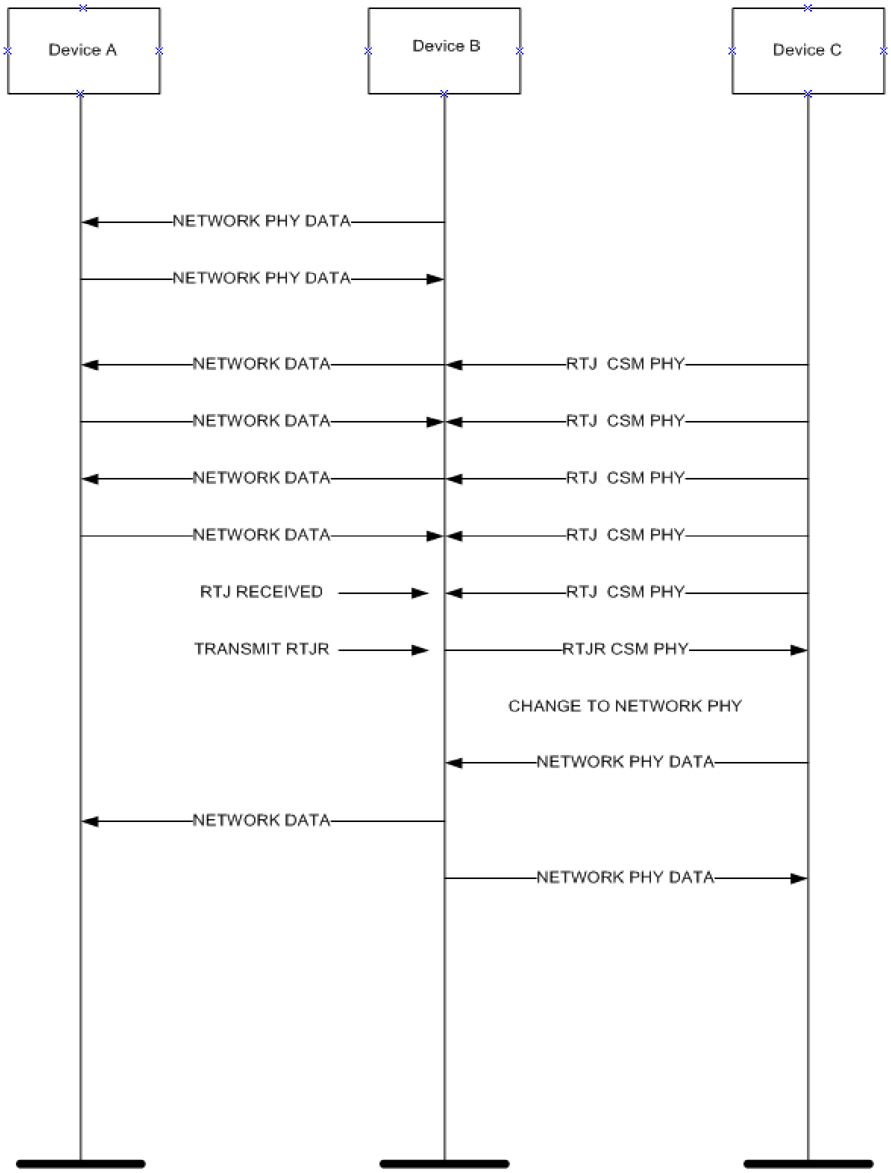


Figure 112b—RTJ/RTJR packet sequence

Annex G

(informative)

Regulatory requirements

G.1 IEEE Std 802.15.4

G.1.2.4 Section 15.247 of FCC CFR47

Insert the following paragraphs at the end of G.1.2.4:

Frequency hopping systems within the bands of 902–928 MHz, 2400–2483.5 MHz, and 5725–5850 MHz 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 will use at least 50 hopping frequencies and the average time of occupancy on any frequency will 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 will use at least 25 hopping frequencies and the average time of occupancy on any frequency will 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 operating in the 2400–2483.5 MHz band use at least 15 non-overlapping channels. The average time of occupancy on any channel cannot 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 cannot 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, the maximum is 1 W. For all other frequency hopping systems in the 2400-2483.5 band, the maximum is 0.125 W.
- For frequency hopping systems operating in the 902-928 MHz band, the maximum is 1 W for systems employing at least 50 hopping channels. The maximum is 0.25 W for systems employing less than 50 hopping channels but at least 25 hopping channels.

Insert after Annex L the following new annex (Annex M):

Annex M

(informative)

Example Usage of Generic PHY Mechanism

M.1 Introduction

With the advances in communication allowing for flexible support of data rates and parameters in modern silicon devices, it has become apparent that standards can be defined to capture these features in a consistent way. Mechanisms, such as the Generic PHY, can provide this purpose.

The generic PHY descriptor includes a collection of PIB attributes. These attributes form the complete set of parameters necessary to define a PHY mode, such as modulation type, data rate, modulation order, and modulation index for FSK operation (see Table 31). An MRFSK-compliant device supports the mandatory PHY mode but may also support the optional modes specified in Table 1a and Table 1b (6.1.1) or other modes derived using the generic PHY descriptor.

The PIB attribute *phyNumSUNPageEntriesSupported* contains the number of SUN operating modes supported by a device, and every supported mode is a table entry in the PIB attribute *phySUNPageEntriesSupported*. In addition, the PIB attribute *phyCurrentSUNPageEntry* specifies the current PHY mode of operation if *phyCurrentPage* equals seven or eight.

M.2 Example of Generic PHY modes

Table M.1 shows an example of a device that supports five Generic PHY defined modes (*phyNumGenericPHYDescriptors*=5). Each Generic PHY descriptor is shown in Table M.1.

Table M.1—Examples of Generic PHY descriptors for a device operating in the 902 MHz band

PIB attribute	PHY mode0	PHY mode1	PHY mode2	PHY mode3	PHY mode4
GenericPHYId	0	1	2	3	4
FirstChannelFreq	902.25 MHz	902.3 MHz	902.4 MHz	902.6 MHz	904.0 MHz
NumChannels	52	85	64	32	32
ChannelSpacing	500 kHz	300 kHz	400 kHz	800 kHz	2 MHz
DataRate	76.8 kb/s	100 kb/s	142.222 kb/s	750 kb/s	250 kb/s
ModulationScheme	FSK	FSK	FSK	OFDM	DSSS
FSKModulationOrder	2-level FSK	2-level FSK	2-level FSK	n/a	n/a

Table M.1—Examples of Generic PHY descriptors for a device operating in the 902 MHz band

FSKModulationIndex	1.0	0.5	1.0	n/a	n/a
FSKBT	n/a	n/a	n/a	n/a	n/a

M.3 Example of SUN Channel Page Usage

A device that supports the 802.15.4d GFSK PHY (all channels), the 802.15.4g FSK PHY mode for the 915 MHz band (mandatory mode and one optional mode), the 802.15.4g FSK PHY mode for the 950 MHz band (all standard defined mandatory and optional modes), the O-QPSK (DSSS) PHY modes for the 915 MHz band (all standard defined modes), and 1 generic PHY defined mode. If the current operating mode of the device is 915 MHz GFSK (SUN PHY), data rate = 200 kbps, it would have the following values for the PIB attributes:

- *phyNumSunPageEntriesSupported* = 4
- *phySunPageEntriesSupported* as shown in Figure M.1
- *phyCurrentSunPageEntry* is shown in Figure M.2
- *phyMaxSunChannelSupported* = 64
- *phySunChannelsSupported* = an eight (64/8) octet array with a bit set for each supported channel.
- *phyCurrentChannel* = a unique value between 0 and (*phyMaxSunChannelSupported*-1)
- *phyCurrentPage* = 7
- *phyChannelsSupported* (lists channels in pages 0-6 supported by the device, R x 32-bit array, R = 1) is shown in Figure M3

0	0	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Page 7					3 = 915 MHz					0=(G)FSK		915 MHz, FSK, mandatory mode and one optional mode supported																			
0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Page 7					0 = 950 MHz					0=(G)FSK		950 MHz, FSK, all 3 standard defined modes supported																			
0	0	1	1	1	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
Page 7					3 = 915 MHz					2 = O-		915 MHz, O-QPSK, all 4 standard defined modes supported																			
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Page 8					reserved					reserved		1 Generic PHY Defined PHY mode supported																			

Figure M.1—SUN page entries supported

0	0	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Page 7					3 = 915 MHz					0=(G)FSK		915 MHz, GFSK, 200 kbps optional mode supported																			

Figure M.2—Current SUN page entry

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Page					Supported Channels																										
0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0

Figure M3—Channels supported

Insert after Annex M the following new annex (Annex N):

Annex N

(informative)

Recommended PHY mode scan parameters

The communications attributes in Table N.1 will be communicated using the channel page index representation.

Table N.1—Recommended PHY mode scan parameters

Index	Class	Band	Domain	Mod	Rate	BT/ FFT	BW (kHz)	Data rate (kb/s)	SD	SI
1	C	220–222	US	GFSK	1.00	0.5	12.5	2.4	10	200
2	A	400–430	Japan	QPSK	0.50	16	200	100	10	1500
3	B	400–430	Japan	GFSK	1.00	0.5	200	50	10	1500
4	A	426–467	Japan	QPSK	0.50	16	200	100	10	1500
5	B	426–467	Japan	GFSK	1.00	0.5	200	50	10	1500
6	C	450–470	US	GPSK	1.00	0.5	12.5	2.4	10	200
7	A	470–510	China	QPSK	0.50	16	200	100	10	1500
8	B	470–510	China	GFSK	1.00	0.5	200	50	10	1500
9	A	863–868	Europe	QPSK	0.75	8	100	50	10	500
10	B	863–870	Europe	GFSK	1.00	0.5	200	50	10	1500
11	A	868–870	Europe	QPSK	0.50	16	200	100	10	1500
12	C	901–902	US	GFSK	1.00	0.5	12.5	2.4	10	200
13	A	902–928	US	QPSK	0.50	16	200	100	10	1500
14	B	902–928	US	FSK	1.00	0.5	200	50	10	1500
15	A	950–956	Japan	QPSK	0.50	16	200	100	10	1500
16	B	950–956	Japan	GFSK	1.00	0.5	200	50	10	1500
17	A	2400	US	QPSK	0.50	16	200	100	10	1500