January, 2010 IEEE P802.15-10-0013-00-004g

IEEE P802.15

Wireless Personal Area Networks

Project IEEE P802.15Working Group forWireless Personal Area Networks (WPANs)

Title Clause 6 OFDM PHY Draft

Date Submitted January 11, 2010

Source Tim Schmidl E-mail: schmidl@ti.com

Re Task Group 15.4g

Abstract This document is a draft of an amendment for Clause 6, containing the parts of the OFDM PHY.

Purpose Review

Draft

6. PHY specification

6.1 General requirements and definitions

Insert the following item to the second dashed list:

— An RF Band agnostic OFDM PHY which supports signal bandwidths from 1MHz down to <100kHz with 9765.625 Hz tone spacing and 128 µs symbol duration.

Change the last paragraph of 6.1 as indicated:

In further additions to the PHYs supported in IEEE Std 802.15.4-2006, and IEEE Std 802.15.4a-2007, and IEEE Std 802.15.4c-2009, ~~two~~ additional PHYs have been added. They are BPSK and GFSK PHYs operating in the Japanese 950 MHz band, two GFSK PHYs operating in the Japanese 400 MHz and 950 MHz bands targeting SUN applications, ~~and~~ a SUN-DSSS-PHY operating in the 780, 868, 915 MHz and 2.4 GHz band, and an OFDM PHY.

6.1.1 Operating frequency range

Insert the following paragraph after the second paragraph in 6.1.1:

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 MHz

— China 783 MHz

— Korea 922 MHz

— TV white spaces

The frequency bands for the OFDM PHY are shown in Table 2.

6.1.2 Channel assignments

6.1.2.1 Channel numbering

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

Table 1—Frequency Bands for OFDM PHY

Frequency band (MHz)
400–430 (Japan) 950.9–955.7 (Japan) 470–510 (China) 783 (China) 922 (Korea) TV White Spaces (Korea)
863–870 (Europe)
902–928 (US) 2400–2483.5 (Worldwide)

6.1.3 Receiver sensitivity definitions

Change the first paragraph of 6.1.7 as indicated:

The receiver sensitivity definitions used throughout this standard are defined in Table 6, with the exception that the receiver sensitivity definition for the OFDM PHY is defined in 6.12a.4.2.

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

6.2.1.1.2 :Appropriate usage

6.2.1.1.3 Effect on receipt

6.2.1.2 PD-DATA.confirm

6.2.1.2.1 Semantics of the service primitive

6.2.1.2.2 When generated

6.2.1.2.3 Appropriate usage

6.2.1.3 PD-DATA.indication

6.2.1.3.1 Semantics of the service primitive

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

6.3 PPDU format

Change the third paragraph of subclause 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, containing the preamble and the SFD for non-OFDM PHY's and containing the short training field and long training field for the OFDM PHY
- A PHY header (PHR), which contains frame control, frame length information and, for UWB PHYs, rate, ranging, and preamble information
- A variable length payload, which carries the MAC sublayer frame (including the FCS)

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

Each OFDM PPDU packet consists of the following basic components:

- A synchronization header which consists of a short training field and a long training field. The~~A~~ Short Training Field (STF)~~, which~~ allows a receiving device to perform automatic gain control (AGC), packet detection, de-assertion of CCA (Clear Channel Assessment) based on CCA-Modes (Mode 1,2 or 3 as defined in 6.12.10) and coarse synchronization. The Long Training Field (LTF) allows a receiving device to do fine synchronization and perform channel estimation.
- ~~A Long Training Field (LTF), which allows a receiving device to do fine synchronization and perform channel estimation~~
- A PHY header (PHR), which contains frame data-rate and frame-length information. The PHY Header shall be encoded at the lowest data-rate supported for each bandwidth option.

- A variable length PSDU, which carries
  - The MAC sub-layer frame (MAC Header, MAC Payload and MAC-CRC-32 as defined in 7.2
  - Convolutional encoder tail-bits (6-zeros) and
  - Zero pad-bits to extend the data fill an integer number of OFDM symbols.

Number of OFDM Symbols			
4	2	M	N
STF	LTF	PHR (see 6.3.4a.2.1)	PSDU
SHR		PHR	PHY payload

Figure 26b—Format of the OFDM PPDU

6.3.1 Preamble field

Insert the following paragraphs after the third paragraph of 6.3.1:

The Preamble field is replaced by the STF and LTF for OFDM, and the STF is defined in 6.3.4a.1.1 and the LTF is defined in 6.3.4a.1.2.

6.3.2 SFD field

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:

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

6.3.3 Frame Length field

Insert the following three new paragraphs after the first paragraph of 6.3.3:

The 4g~~Frame Length field is replaced by the~~ PHY Header (PHR) for the OFDM PHY consists of the frame length field and frame control bits. The PHR for the OFDM PHY is described in 6.3.4a.2.1.

6.3.4 PSDU field

6.3.4a .Field descriptions for the OFDM PHY

6.3.4a.1 Preamble field

The Preamble field is replaced by the STF and LTF for OFDM, and the STF is defined in 6.3.4a.1.1 and the LTF is defined in 6.3.4a.1.2.

6.3.4a.1.1 Short Training field for OFDM

Frequency Domain STF:

The STF for the five scalable bandwidth OFDM options are defined by the following Matlab equations in the Frequency Domain:

STF_freq(Option-1) = sqrt(108/24)*[0, zeros(1,7), -1-j, zeros(1,7), -1-j, zeros(1,7), 1+j, zeros(1,7), 1+j, zeros(1,7), 1+j zeros(1,7), 1+j, zeros(1,15), zeros(1,16), 1+j, zeros(1,7), -1-j, zeros(1,7), 1+j, zeros(1,7), -1-j, zeros(1,7), -1-j, zeros(1,7), 1+j, zeros(1,7)];

Note: STF Option-1 will be modified to have non-zero elements every 4 tones so that the repetition period is 1/4 of the useful part of the OFDM symbol.

STF_freq(Option-2) = sqrt(52/24)*[0, zeros(1,3), -1-j, zeros(1,3), -1-j, zeros(1,3), 1+j, zeros(1,3), 1+j, zeros(1,3), 1+j, zeros(1,3), 1+j, zeros(1,7), zeros(1,8),1+j, zeros(1,3) -1-j, zeros(1,3) 1+j, zeros(1,3) -1-j, zeros(1,3) -1-j, zeros(1,3) 1+j, zeros(1,3)];

STF_freq(Option-3) = sqrt(26/12)*[0,zeros(1,3),-1-j, zeros(1,3), 1+j, zeros(1,3), 1+j, zeros(1,3), zeros(1,4), 1+j, zeros(1,3),-1-j,zeros(1,3),-1-j,zeros(1,3)]

STF_freq(Option-4) = sqrt(14/12)*[0,0,-1-j,0,1+j,0,1+j,0,0,0,1+j,0,-1-j,0,-1-j,0]

STF_freq(Option-5) = sqrt(6/4)*[0,0,1+j,0,0,0,-1-j,0]

Alternative STF sequences with low peak-to-average power ratios are given below.

STF_freq(Option-1) = sqrt(104/24)*[0, 0, 0, 0,-1, 0, 0, 0,-1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0,-1, 0, 0, 0,-1, 0, 0, 0, 1, 0, 0, 0,-1, 0, 0, 0, 1, 0, 0, 0,-1, 0, 0, 0, 1, 0, 0, 0,-1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,-1, 0, 0, 0,-1, 0, 0, 0,-1, 0, 0, 0,-1, 0, 0, 0,-1, 0, 0, 0,-1, 0, 0, 0,-1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0,-1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0,-1, 0, 0, 0]

STF_freq(Option-2) = sqrt(52/12)*[0, 0, 0, 0, 1, 0, 0, 0,-1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0,-1, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,-1, 0, 0, 0,-1, 0, 0, 0,-1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0]

STF_freq(Option-3) = sqrt(26/6)*[0, 0, 0, 0,-1, 0, 0, 0, 1, 0, 0, 0,-1, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0]

STF_freq(Option-4) = sqrt(14/6)*[0, 0,-1, 0, 1, 0,-1, 0, 0, 0, 1, 0, 1, 0, 1, 0]

STF_freq(Option-5) = sqrt(6/2)*[0, 0,-1, 0, 0, 0, 1, 0]

[Editor's note: the STF sequences should be put in table form when the sequences are decided]

(Figure 27c)

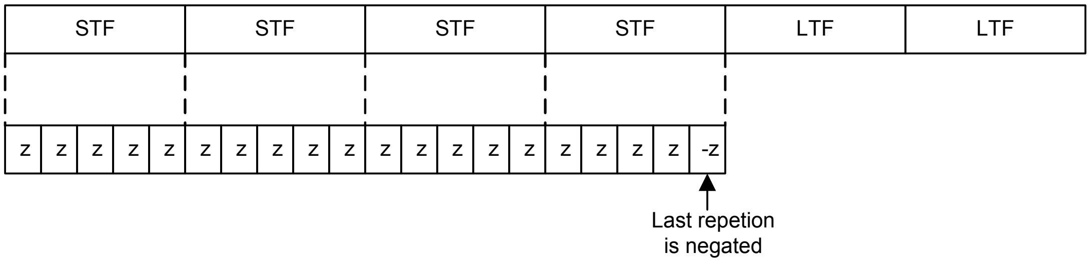

Figure 27c—Structure of STF for OFDM

There are 4 STF OFDM symbols, and the last 1/4 of the useful part of the 4th OFDM symbol is negated in the time domain.

STF Normalization:

The STF uses lesser number of tones than the data-portion. Hence, normalization of the frequency domain STF is required to ensure that the STF power is same as the rest of the data-frame. The normalization value 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.

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))

Time Domain STF Repetition:

The time-domain STF is repeated to fill 4-OFDM symbols (512us) before transmission.

6.3.4a.1.2 Long Training field for OFDM

Frequency Domain LTF:

The LTF for the five scalable bandwidth OFDM options are defined by the following Matlab equations in the Frequency Domain:

LTF_freq(Option-1)= {0,0,-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, zeros(1,17),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,-1,1,0}

LTF_freq(Option-2)= {0,1,-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,zeros(1,11),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}

LTF_freq(Option-3)= {0,1,-1,-1,1,1,-1,1,-1,1,-1,-1,-1,-1,zeros(1,5),1,1,-1,-1,1,1,-1,1,-1,1,1,1,1}

LTF_freq(Option-4)= {0,1,-1,-1,1,1,-1,1,zeros(1,1),-1,1,-1,1,1,-1,1}

LTF_freq(Option-5)= {0,1,-1,-1, zeros(1,1),1,-1,1}

Alternative LTF sequences with low peak-to-average power ratios are given below:

LTF_freq(Option-1)= [0, 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,zeros(1,23), -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]

LTF_freq(Option-2)= [0,1,-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, zeros(1,11), -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]

LTF_freq(Option-3)= [0, -1,-1, 1,-1, 1, 1,-1,-1, 1, 1,-1,-1, 1, zeros(1,5), 1,-1, 1,-1, 1, 1, 1, 1, 1, 1, 1, 1,-1]

LTF_freq(Option-4)= [0, -1, 1, 1, 1,-1,-1,-1, 0, 1,-1, 1, 1,-1, 1, 1]

LTF_freq(Option-5)= [0, -1, 1,-1, 0, 1, 1, 1]

[Editor's note: the LTF sequences should be put in table form when the sequences are decided]

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))

Time Domain LTF Repetition:

The time-domain LTF is repeated to fill 2-OFDM symbols (256us) before transmission.

6.3.4a.2 Frame Length field

The Frame Length field is replaced by the PHY Header (PHR) for the OFDM PHY. The PHR for the OFDM PHY is described in 6.3.4a.2.1.

6.3.4a.2.1 PHY Header for OFDM

The PHY Header (PHR) field 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 6.12a.1.

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

The PHY header fields include:

- Rate field specifies the data rate of the payload frame (5 bits)

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

Figure 27d—PHY header fields for OFDM

- 1 Reserved bit after the Rate field
- Length specifies the length of the payload (11 bits)
- 2 Reserved bits after the Length field
- Scrambling seed (2 bits)
- 1 Reserved bit after the Scrambler field
- Header Check sequence 8 bit CRC taken over the data fields only
- Tail bits for Viterbi decoder flushing

All reserved bits shall be set to “0” value.

<Editor’s Note: The PHY Header would occupy M OFDM symbols. The value of M varies from 2 to 4 depending on the OFDM bandwidth option. The exact value of M would be derived once the PHY header is frozen.>

6.4 PHY constants and PIB attributes

6.4.1 PHY constants

6.4.2 PHY PIB attributes

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 subclause (6.12a):

6.12a OFDM PHY specification

6.12a.1 Data rates

There are 5 OFDM options with 5 different recommended FFT sizes of 128, 64, 32, 16, and 8.

The device shall support one or several of the data rates shown in Table 75a:

Table 75a—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 repetition)	93.75					kbps
MCS1 (BPSK rate 1/2 with 2x repetition)	187.5	93.75	46.88			kbps
MCS2 (BPSK rate 1/2 OR QPSK rate 1/2 and 2x repetition)	375	187.5	93.75	46.88		kbps
MCS3 (QPSK rate 1/2 OR DCM QPSK rate 1/2)	750	375	187.5	93.75		kbps
MCS4 (QPSK rate 3/4 OR DCM QPSK rate 3/4)		562.5	281.25	140.63	46.88	kbps
MCS5 (16-QAM rate 1/2)		750	375	187.5	62.5	kbps
MCS6 (16-QAM rate 3/4)			562.5	281.25	93.75	

6.12a.2 Data transfer

6.12a.3 Modulation and coding

6.12a.3.1 Reference modulator diagram

(Figure 65o) [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.]

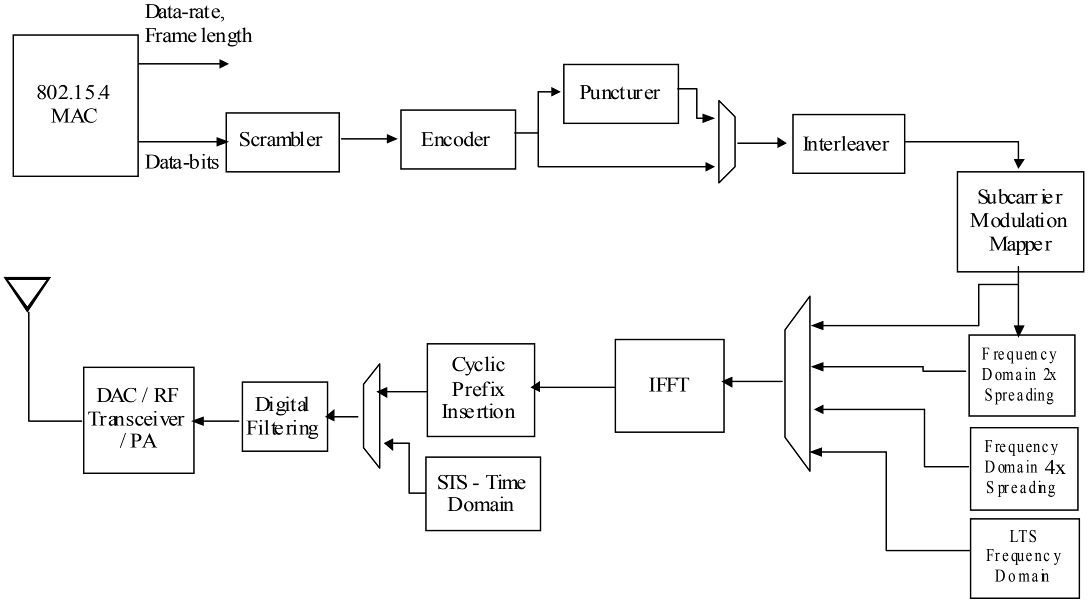

Figure 65o—Reference modulator diagram for OFDM

6.12a.3.2 Bit-to-symbol mapping

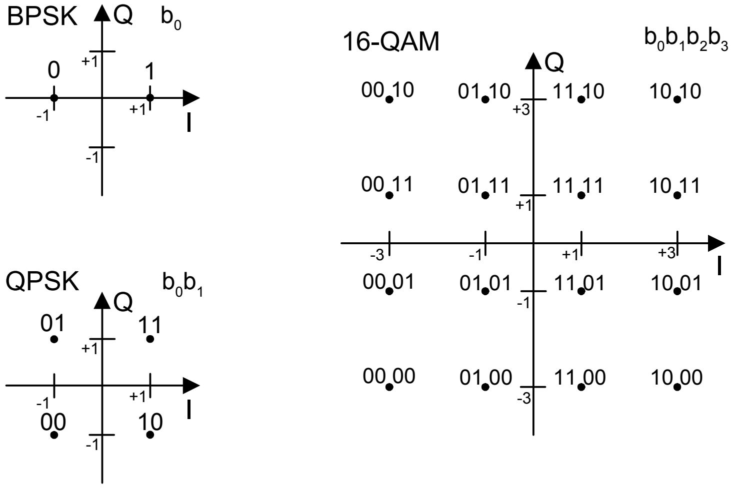

Figure 65p—Bit to symbol mapping for OFDM

For BPSK, b_0 determines the I value, as illustrated in Table 75b. For QPSK, b_0 determines the I value and b_1 determines the Q value, as illustrated in Table 75c. For 16-QAM, b_0b_1 determines the I value and b_2b_3

determines the Q value, as illustrated in Table 75d.

The output values, d, are formed by multiplying the resulting (I+jQ) value by a normalization factor K_{MOD}, as described in Equation (1).

$$d = (I + jQ) \times K_{MOD} \tag{1}$$

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

Table 75b—BPSK encoding table

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

Table 75c—QPSK encoding table

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

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

Table 75d—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

In the case that dual-carrier modulation (DCM) is used, 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

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

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

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 4 bits. Each group is represented as ($b[g(k)]$, $b[g(k)+1]$, $b[g(k) + N]$, $b[g(k) + N+1]$), where $k \in [0, N-1]$ and

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

2) Each group of 4 bits ($b[g(k)]$, $b[g(k)+1]$, $b[g(k) + N]$, $b[g(k) + N+1]$) shall be mapped onto a four-dimensional constellation, as shown in the figure below, and converted into two complex numbers ($d[k]$, $d[k + N]$). 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.

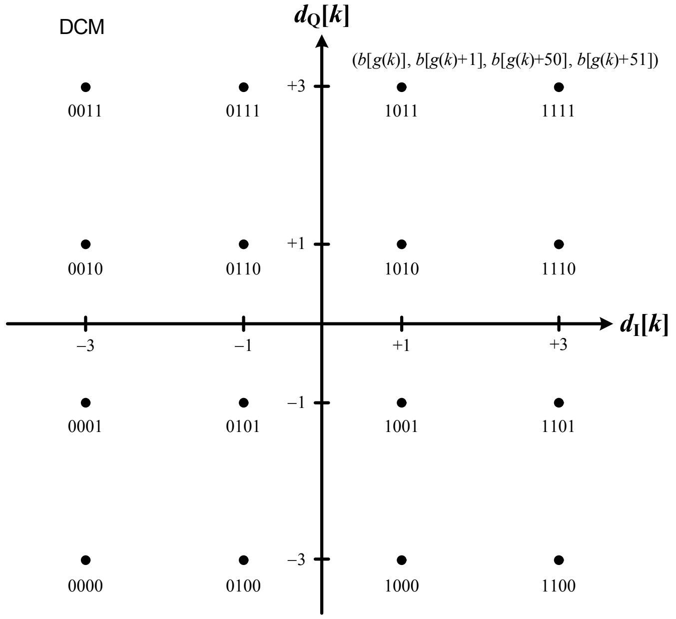

Figure 65q—DCM mapping for d[k]

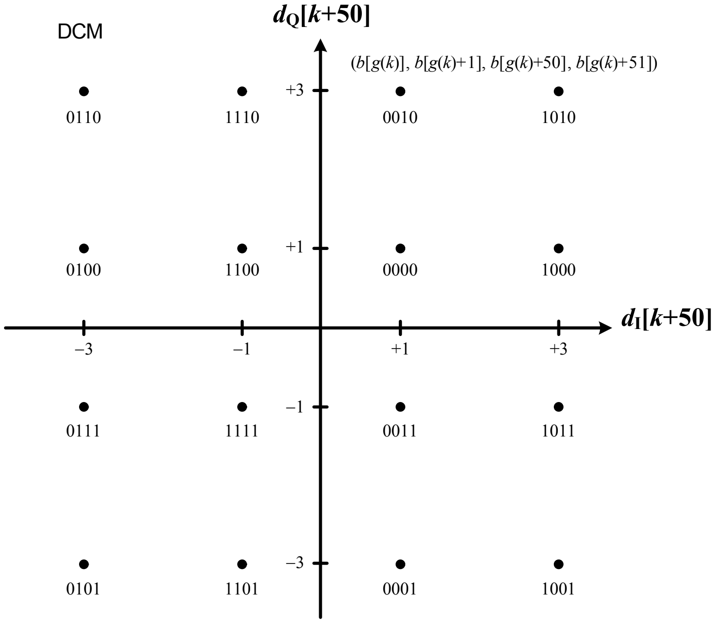

Figure 65r—DCM mapping for d[k+N]

Table 75f—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

6.12a.3.3 Modulation parameters

6.12a.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 Figure 65s.

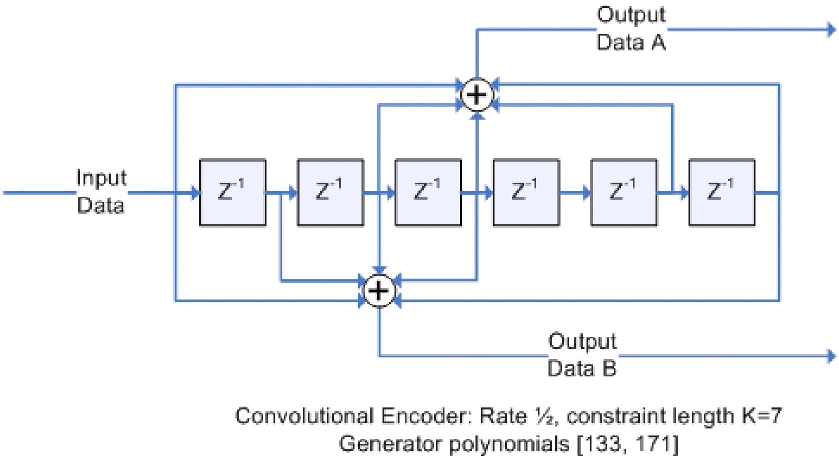

Figure 65s—Rate 1/2 convolutional encoder

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

Figure 65t—Puncturing for rate 3/4

6.12a.3.5 Interleaver

The interleaving is defined for each one of the 5 OFDM options, through the following Matlab scripts:

$i = (Ncbps/Nrow)(k \bmod Nrow) + floor(k/Nrow)$, $k = 0, 1, 2, \ldots Ncbps - 1$

$j = s*floor(i/s) + (i + Ncbps - floor(Nrow*i/Ncbps)) \bmod s$, $i = 0, 1, 2, \ldots, Ncbps$

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

OFDM Option 1:

$Ncbps = 96*\{1,2\}$

Nrow = TBD

OFDM Option 2:

$Ncbps = 48*\{1,2,4\}$

Nrow = TBD

OFDM Option 3:

$Ncbps = 24*\{1,2,4\}$

Nrow = TBD

OFDM Option 4:

$Ncbps = 12*\{1,2,4\}$

Nrow = TBD

OFDM Option 5:

$Ncbps = 6*\{1,2,4\}$

Nrow = TBD

6.12a.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 2 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 $N_d/2$

~~The spreading is performed by repeating the data on one side of the DC tone to the other side, using the conjugate value of the data.~~

~~Figure 65u indicates how the left half of the spectrum is replicated using conjugated versions of the PSK symbol~~

Figure 65u—~~Frequency spreading by 2x~~

Frequency spreading by 4x

~~Frequency spreading by 4x can be performed in 2 steps. First the lower half of the negative frequency tones can be copied to the upper half of the negative frequency tones. In the second step the left half of the spectrum is replicated using conjugated versions of the PSK symbols as is done for 2x frequency spreading. The pilot tones (shown with a dashed line in Figure 65v) are not replicated in Step 1.~~

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 $N_d/4$

Figure 65v—~~Frequency spreading by 4x~~

6.12a.3.7 Pilot Tones / Null Tones

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

Table 75g—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

OFDM Option 1:

P-54,54 = {0, 0, 0, 0, 0, -1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, 0, 0, 0, 0, 0};

The pilot tone positions within each OFDM symbol are TBD. The data carried on the pilot tones shall be determined by a pseudo-noise sequence which is TBD.

6.12a.3.8 Cyclic Prefix

A cyclic prefix shall be inserted before each OFDM symbol. The duration of the CP shall be 1/4 the symbol rate (25.6 ~~u~~µs). It is a replication of the last part of the data symbol.

6.12a.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.

6.12a.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 6 bits are appended to the message, in order to accommodate the TAIL bits, as described in 6.12a.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:

$$N_{SYM} = \text{Ceiling}\left((8 \times \text{LENGTH} + 6)/N_{DBPS}\right)$$

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

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

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.

6.12a.3.11 Pulse shape

6.12a.4 Radio specification

6.12a.4.1 Transmit PSD Mask

The OFDM transmit PSD mask is TBD.

6.12a.4.2 Receiver minimum input level sensitivity

The packet error rate (PER) shall be less than 10% at a PSDU length of 1000 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).

6.12a.4.3 Adjacent channel rejection

The adjacent channel rejection for OFDM is TBD.

6.12a.4.4 Alternate adjacent channel rejection

The alternate adjacent channel rejection for OFDM is TBD.

6.12.2 TX-to-RX turnaround time

6.12.3 RX-to-TX turnaround time

6.12.4 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, and the OFDM PHY transmitter as described in 6.12a, 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.

6.12.5 Transmit center frequency tolerance

6.12.6 Transmit power

6.12.7 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~~at~~ a PSDU length of 1000 bytes with a receiver maximum input level greater than or equal to -20 dBm.

6.12.8 Receiver ED

6.12.9 Link quality indicator (LQI)

6.12.10 Clear channel assessment (CCA)