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Abstract	A high rate WPAN with data rates from 55 Mbps to 480 Mbps is proposed.
Purpose	Discussion
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Release	

Physical Layer Submission to 802.15 Task Group 3a: Multi-band Orthogonal Frequency Division Multiplexing

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1 UWB Physical Layer

1.1 Introduction

This clause specifies the PHY entity for a UWB system that utilizes the unlicensed 3.1 – 10.6 GHz UWB band, as regulated in the United States by the Code of Federal Regulations, Title 47, Section 15. The UWB system provides a wireless PAN with data payload communication capabilities of 55, 80, 110, 160, 200, 320, and 480 Mb/s. The support of transmitting and receiving at data rates of 55, 110, and 200 Mb/s is mandatory. The proposed UWB system employs orthogonal frequency division multiplexing (OFDM). The system uses a total of 122 sub-carriers that are modulated using quadrature phase shift keying (QPSK). Forward error correction coding (convolutional coding) is used with a coding rate of 11/32, ½, 5/8, and ¾. The proposed UWB system also supports multiple modes of operations: a mandatory 3-band mode (Mode 1), and an optional 7-band mode (Mode 2).

1.1.1 Overview of the proposed UWB system description

1.1.1.1 Mathematical description of the signal

The transmitted signals can be described using a complex baseband signal notation. The actual RF transmitted signal is related to the complex baseband signal as follows:

$$r_{RF}(t) = \mathrm{Re}\left\{ \sum_{k=0}^{N-1} r_k(t - kT_{SYM}) \exp(j2\pi f_k t) \right\},$$

where $\mathrm{Re}(\cdot)$ represents the real part of a complex variable, $r_k(t)$ is the complex baseband signal of the k^{th} OFDM symbol and is nonzero over the interval from 0 to T_{SYM}, N is the number of OFDM symbols, T_{SYM} is the symbol interval, and f_k is the center frequency for the k^{th} band. The exact structure of the k^{th} OFDM symbol depends on its location within the packet:

$$r_k(t) = \begin{cases} r_{preamble,k}(t) & 0 \le k < N_{preamble} \\ r_{header,k-N_{preamble}}(t) & N_{preamble} \le k < N_{header} \\ r_{data,k-N_{preamble}}(t) & N_{header} \le k < N_{data} \end{cases}.$$

The structure of each component of $r_k(t)$ as well as the offsets $N_{preamble}$, N_{header}, and N_{data} will be described in more detail in the following sections.

All of the OFDM symbols $r_k(t)$ can be constructed using an inverse Fourier transform with a certain set of coefficient C_n, where the coefficients are defined as either data, pilots, or training symbols:

$$r_k(t) = \begin{cases} 0 & t \in [0, T_{CP}] \\ \sum_{n=-N_{ST}/2}^{N_{ST}/2} C_n \exp(j2\pi n\Delta_f)(t - T_{CP}) & t \in [T_{CP}, T_{FFT} + T_{CP}] \\ 0 & t \in [T_{FFT} + T_{CP}, T_{FFT} + T_{CP} + T_{GI}] \end{cases} .$$

The parameters Δ_f and N_{ST} are defined as the subcarrier frequency spacing and the number of total subcarriers used, respectively. The resulting waveform has a duration of $T_{FFT} = 1/\Delta_f$. Shifting the time by T_{CP} creates the "circular prefix" which is used in OFDM to mitigate the effects of multipath. The parameter T_{GI} is the guard interval duration.

1.1.1.2 Discrete-time implementation considerations

The following description of the discrete time implementation is informational. The common way to implement the inverse Fourier transform is by an inverse Fast Fourier Transform (IFFT) algorithm. If, for example, a 128-point IFFT is used, the coefficients 1 to 61 are mapped to the same numbered IFFT inputs, while the coefficients –61 to –1 are copied into IFFT inputs 67 to 127. The rest of the inputs, 62 to 66 and the 0 (DC) input, are set to zero. This mapping is illustrated in Figure 1. After performing the IFFT, a zero-padded prefix of length 32 is pre-appended to the IFFT output and a guard interval is added at the end of the IFFT output to generate an output with the desired length of 165 samples.

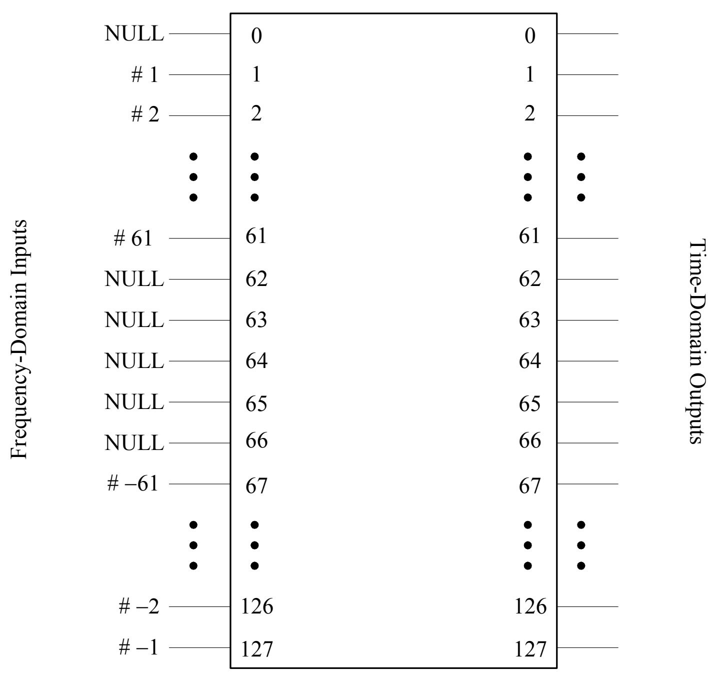


Figure 1 – Input and outputs of IFFT

1.1.2 Scope

This subclause describes the PHY services provided to the IEEE 802.15.3 wireless PAN MAC. The OFDM PHY layer consists of two protocol functions, as follows:

a) A PHY convergence function, which adapts the capabilities of the physical medium dependent (PMD) system to the PHY service. This function is supported by the physical layer convergence procedure (PLCP), which defined a method of mapping the IEEE 802.15 PHY sublayer service data units (PSDU) into a framing format suitable for sending and receiving user data and management information between two or more stations using the associated PMD system.

b) A PMD system whose function defines the characteristics and method of transmitting and receiving data through a wireless medium between two or more stations, each using the OFDM system.

1.1.3 UWB PHY function

The UWB PHY contains three functional entities: the PMD function, the PHY convergence function, and the layer management function. The UWB PHY service is provided to the MAC through the PHY service primitives.

1.1.3.1 PLCP sublayer

In order to allow the IEEE 802.15.3 MAC to operate with minimum dependence on the PMD sublayer, a PHY convergence sublayer is defined. This function simplifies the PHY service interface to the IEEE 802.15.3 MAC services.

1.1.3.2 PMD sublayer

The PMD sublayer provides a means to send and receive data between two or more stations.

1.1.3.3 PHY management entity (PLME)

The PLME performs management of the local PHY functions in conjunction with the MAC management entity.

1.2 UWB PHY specific service parameter list

1.2.1 Introduction

Some PHY implementations require medium management state machines running in the MAC sublayer in order to meet certain PMD requirements. This PHY-dependent MAC state machines reside in a sublayer defined as the MAC sublayer management entity (MLME). In certain PMD implementations, the MLME may need to interact with the PLME as part of the normal PHY SAP primitives. These interactions are defined by the PLME parameter list currently defined in the PHY services primitives as TXVECTOR and RXVECTOR. The list of these parameters, and the values they may represent, are defined in the PHY specification for each PMD. This subclause addresses the TXVECTOR and RXVECTOR for the OFDM PHY.

1.2.2 TXVECTOR parameters

The parameters in Table 1 are defined as part of the TXVECTOR parameter list in the PHY-TXSTART.request service primitive.

Table 1 – TXVECTOR parameters

Parameter	Associate Primitive	Value
LENGTH	PHY-TXSTART.request (TXVECTOR)	1–4095
DATARATE	PHY-TXSTART.request (TXVECTOR)	55, 80, 110, 160, 200, 320, and 480 (Support for 55, 110, and 200 data rates is mandatory.)
SCRAMBLER_INIT	PHY-TXSTART.request (TXVECTOR)	Scrambler initialization: 2 null bits
TXPWR_LEVEL	PHY-TXSTART.request (TXVECTOR)	1–8

1.2.2.1 TXVECTOR LENGTH

The allowed values for the LENGTH parameter are in the range 1–4095. This parameter is used to indicate the number of octets in the frame payload (which does not include the FCS), which the MAC is currently requesting the PHY to transmit. This value is used by the PHY to determine the number of octets transfers that will occur between the MAC and the PHY after receiving a request to start the transmission.

1.2.2.2 TXVECTOR DATARATE

The DATARATE parameter describes the bit rate at which the PLCP shall transmit the PSDU. Its value can be any of the rates defined in Table 1. Data rates of 55, 110, and 200 Mb/s shall be supported; other rates may also be supported.

1.2.2.3 TXVECTOR SCRAMBLER_INIT

The SCRAMBLER_INIT parameter consists of 2 null bits used for the scrambler initialization.

1.2.2.4 TXVECTOR TXPWR_LEVEL

The allowed values for the TXPWR_LEVEL parameter are in the range from 1–8. This parameter is used to indicate which of the available TxPowerLevel attributes defined in the MIB shall be used for the current transmission.

1.2.3 RXVECTOR parameters

The parameters in Table 2 are defined as part of the RXVECTOR parameter list in the PHY-RXSTART.indicate service primitive.

Table 2 – RXVECTOR parameters

Parameter	Associate Primitive	Value
LENGTH	PHY-RXSTART.indicate (RXVECTOR)	1–4095
RSSI	PHY-RXSTART.indicate (RXVECTOR)	0–RSSI maximum
DATARATE	PHY-RXSTART.indicate (RXVECTOR)	55, 80, 110, 160, 200, 320, and 480

1.2.3.1 RXVECTOR LENGTH

The allowed values for the LENGTH parameter are in the range 1–4095. This parameter is used to indicate the value contained in the LENGTH field that the PLCP has received in the PLCP header. The MAC and the PLCP will use this value to determine the number of octet transfers that will occur between the two sublayers during the transfer of the received PSDU.

1.2.3.2 RXVECTOR RSSI

The allowed values for the receive signal strength indicator (RSSI) parameter are in the range from 0 through RSSI maximum. This parameter is a measure by the PHY sublayer of the energy observed at the antenna used to receive the current PSDU. RSSI shall be measured during the reception of the PLCP preamble. RSSI is to be used in a relative manner, and it shall be a monotonically increasing function of the received power.

1.2.3.3 RXVECTOR DATARATE

DATARATE shall represent the data rate at which the current PPDU was received. The allowed values of the DATARATE are 55, 80, 110, 160, 200, 320, or 480.

1.3 UWB PLCP sublayer

1.3.1 Introduction

This subclause provides a method for converting the PSDUs to PPDUs. During the transmission, the PSDU shall be provided with a PLCP preamble and header to create the PPDU. At the receiver, the PLCP preamble and header are processed to aid in the demodulation, decoding, and delivery of the PSDU.

1.3.2 PLCP frame format

Figure 2 shows the format for the PHY frame including the PLCP preamble, PLCP header (PHY header, MAC header, header check sequence, tail bits, and pad bits), MAC frame body (frame payload plus FCS), tail bits, and pad bits. Additionally, an optional band extension sequence will be included after the PLCP header when frame payload is transmitted using Mode 2.

The PHY layer first pre-appends the PHY header plus the tail bits to the MAC header and then calculates the HCS over the combined headers and tail bits. The tail bits are added after the PHY header in order to return the convolutional encoder to the "zero state". The resulting HCS is appended to the end of the MAC header along with an additional set of tail bits. Pad bits are also added after the tail bits in order to align the data stream on an OFDM symbol boundary.

Tail bits are also added to the MAC frame body (i.e., the frame payload plus FCS) in order to return the convolutional encoder to the "zero state". If the size of the MAC frame body plus tail bits are not an integer multiple of the bits/OFDM symbol, then pad bits (PD) are added to the end of the tail bits in order to align the data stream on the OFDM symbol boundaries.

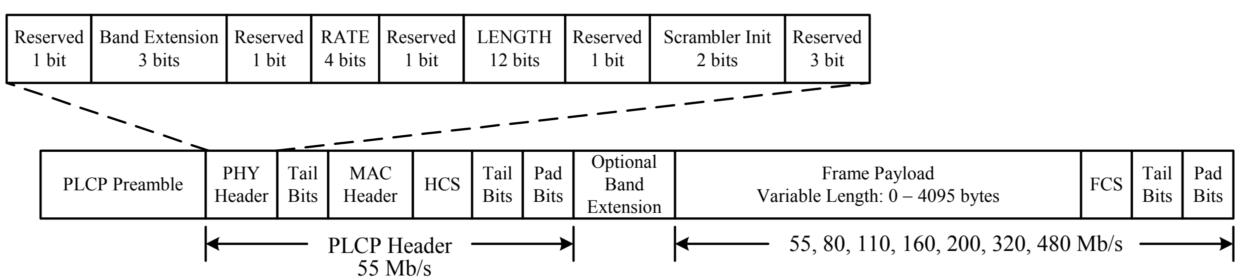


Figure 2 – PLCP frame format for a Mode 1 device

The PLCP preamble is sent first, followed by the PLCP header, followed by an optional band extension sequence, followed by the frame payload, the FCS, the tail bits, and finally the pad bits. As shown in Figure 2, the PLCP header is always sent at an information data rate of 55 Mb/s. The PLCP header is always transmitted using Mode 1. The remainder of the PLCP frame (frame payload, FCS, tail bits, and pad bits) is sent at the desired information data rate of 55, 80, 110, 160, 200, 320, or 480 Mb/s using either Mode 1 or Mode 2.

1.3.2.1 RATE-dependent parameters

The data rate dependent modulation parameters are listed in Table 3.

Table 3 – Rate-dependent parameters

Data Rate (Mb/s)	Modulation	Coding rate (R)	Conjugate Symmetric Input to IFFT	Time Spreading	Overall Spreading Gain	Coded bits per OFDM symbol (N_{CBPS})
55	QPSK	11/32	Yes	Yes	4	100
80	QPSK	½	Yes	Yes	4	100
110	QPSK	11/32	No	Yes	2	200
160	QPSK	½	No	Yes	2	200
200	QPSK	5/8	No	Yes	2	200
320	QPSK	½	No	No	1	200
480	QPSK	¾	No	No	1	200

1.3.2.2 Timing-related parameters

A list of the timing parameters associated with the OFDM PHY is listed in Table 4.

Table 4 – Timing-related parameters

Parameter	Value
N_{SD}: Number of data subcarriers	100
N_{SDP}: Number of defined pilot carriers	12
N_{SG}: Number of guard carriers	10
N_{ST}: Number of total subcarriers used	122 (= $N_{SD} + N_{SDP} + N_{SG}$)
Δ_F: Subcarrier frequency spacing	4.125 MHz (= 528 MHz/128)
T_{FFT}: IFFT/FFT period	242.42 ns ($1/\Delta_F$)
T_{CP}: Cyclic prefix duration	60.61 ns (= 32/528 MHz)
T_{GI}: Guard interval duration	9.47 ns (= 5/528 MHz)
T_{SYM}: Symbol interval	312.5 ns ($T_{CP} + T_{FFT} + T_{GI}$)

1.3.3 PLCP preamble

A standard PLCP preamble shall be added prior to the PLCP header to aid receiver algorithms related to synchronization, carrier-offset recovery, and channel estimation. The standard PLCP preamble, which is shown in Figure 3, consists of three distinct portions: packet synchronization sequence, frame synchronization sequence, and the channel estimation sequence. The packet synchronization sequence shall be constructed by successively appending 21 periods, denoted as {PS_0, PS_1, …, PS_{20} }, of a time-domain sequence. Each piconet will use a distinct time-domain sequence. These time-domain sequences are defined in Table 5 through Table 8. Each period of the timing synchronization sequence shall be constructed by pre-appending 32 “zero samples” and by appending a guard interval of 5 “zero samples” to the sequences defined in Table 5 through Table 8. This portion of the preamble can be used for packet detection and acquisition, coarse carrier frequency estimation, and coarse symbol timing.

Similarly, the frame synchronization sequence shall be constructed by successively appending 3 periods, denoted as {FS_0, FS_1, FS_2}, of an 180 degree rotated version of the time-domain sequence specified in Table 5 through Table 8. Again, each period of the frame synchronization sequence shall be constructed by pre-appending 32 “zero samples” and by appending a guard interval of 5 “zero samples” to the sequences defined in Table 5 through Table 8. This portion of the preamble can be used to synchronize the receiver algorithm within the preamble.

Finally, the channel estimation sequence shall be constructed by successively appending 6 periods, denoted as {CE_0, CE_1, …, CE_5}, of the OFDM training symbol. This training symbol is generated by passing the frequency-domain sequence, defined in Table 9, though the IFFT, and pre-appending the output with 32 “zero samples” and appending and a guard interval consisting of 5 “zero samples” to the resulting time-domain output. This portion of the preamble can be used to estimate the channel frequency response, for fine carrier frequency estimation, and fine symbol timing.

N.B.:The time domain sequences in Tables 5-8 should be normalized appropriately in order to have the same average power as the signals which are defined in the frequency domain (and are thus passed through an IFFT operation), such as the channel estimation sequence defined in Table 9, and the payload samples.

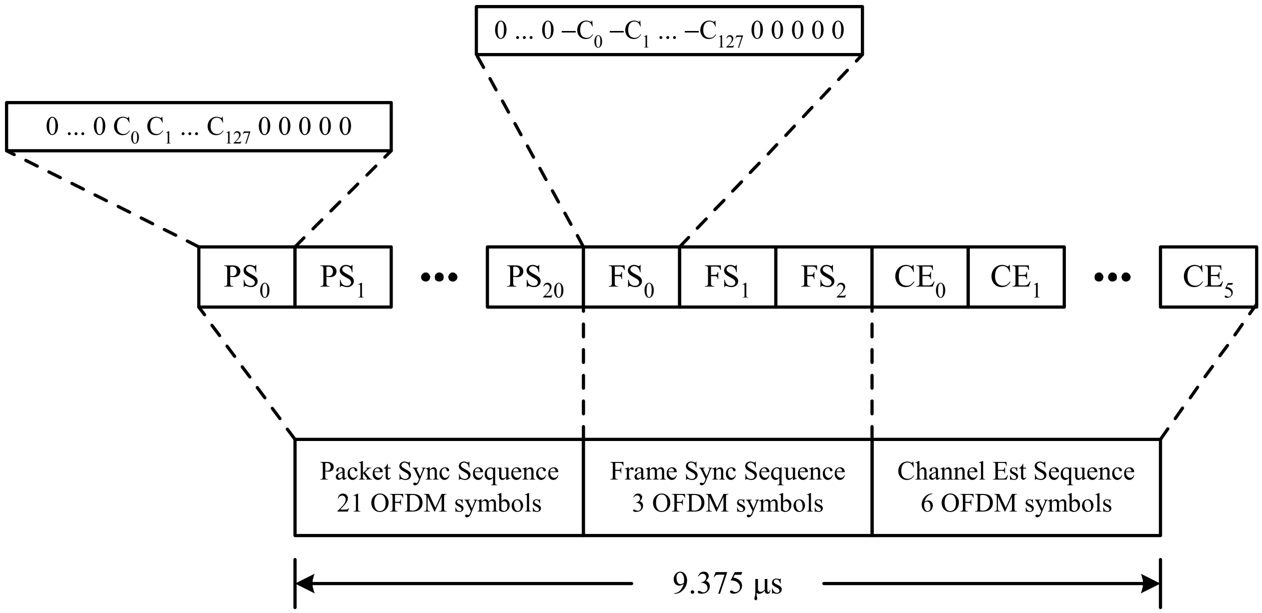


Figure 3 – Standard PLCP preamble format

In addition to a standard PLCP preamble, a streaming-mode PLCP preamble is also defined in this section. In the streaming packet mode, the first packet shall use the standard PLCP preamble, while the remaining packets (second packet and on), which are separated by a MIFS time, shall use the streaming-mode PLCP preamble instead of the standard PLCP preamble. The streaming-mode PLCP preamble, which is shown in Figure 4, consists of three distinct portions: packet synchronization sequence, frame synchronization sequence, and the channel estimation sequence. The packet synchronization sequence shall be constructed by successively appending 6 periods, denoted as $\{PS_0, PS_1, \ldots, PS_5\}$, of a time-domain sequence. Each piconet will use a distinct time-domain sequence. These time-domain sequences are defined in Table 5 through Table 8. Each period of the timing synchronization sequence shall be constructed by pre-appending 32 "zero samples" and by appending a guard interval of 5 "zero samples" to the sequences defined in Table 5 through Table 8. This portion of the preamble can be used for packet detection and acquisition, coarse carrier frequency estimation, and coarse symbol timing.

Similarly, the frame synchronization sequence shall be constructed by successively appending 3 periods, denoted as $\{FS_0, FS_1, FS_2\}$, of an 180 degree rotated version of the time-domain sequence specified in Table 5 through Table 8. Again, each period of the frame synchronization sequence shall be constructed by pre-appending 32 "zero samples" and by appending a guard interval of 5 "zero samples" to the sequences defined in Table 5 through Table 8. This portion of the preamble can be used to synchronize the receiver algorithm within the preamble.

Finally, the channel estimation sequence shall be constructed by successively appending 6 periods, denoted as $\{CE_0, CE_1, \ldots, CE_5\}$, of the OFDM training symbol. This training symbol is generated by passing the frequency-domain sequence, defined in Table 9, though the IFFT, and pre-appending the output with 32 "zero samples" and appending and a guard interval consisting of 5 "zero samples" to the resulting time-domain output. This portion of the preamble can be used to estimate the channel frequency response, for fine carrier frequency estimation, and fine symbol timing.

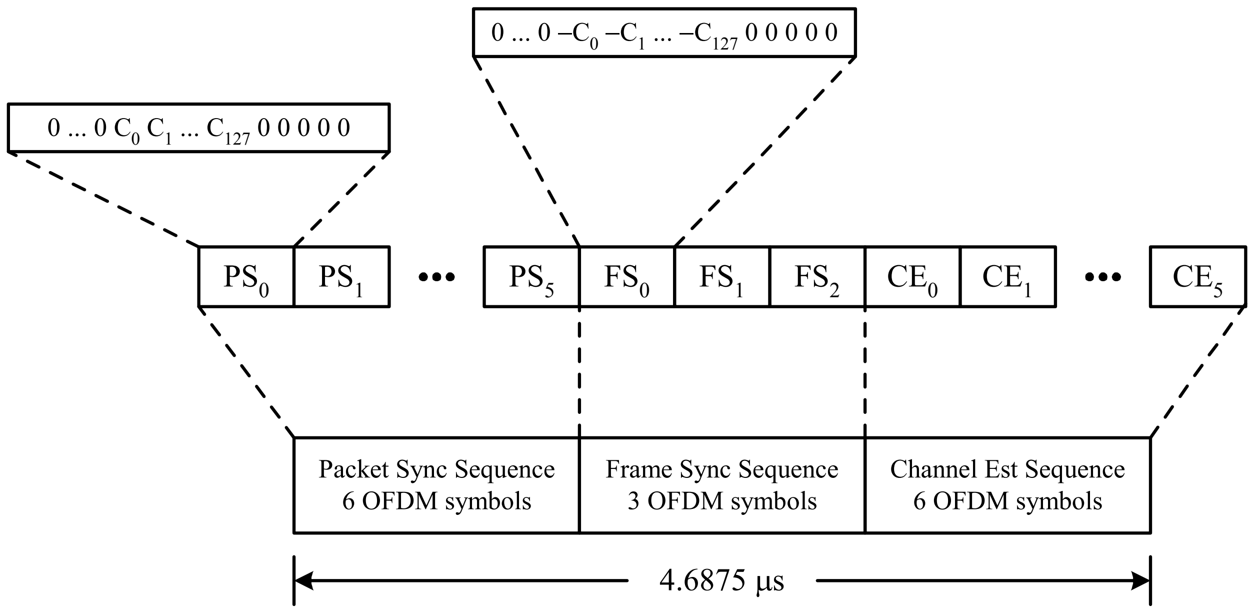


Figure 4 – Streaming-mode PLCP preamble format for a Mode 1 device

Table 5 – Time-domain packet synchronization sequence for Preamble Pattern 1

Sequence Element	Value	Sequence Element	Value	Sequence Element	Value	Sequence Element	Value
C_0	0.6564	C_{32}	-0.0844	C_{64}	-0.2095	C_{96}	0.4232
C_1	-1.3671	C_{33}	1.1974	C_{65}	1.1640	C_{97}	-1.2684
C_2	-0.9958	C_{34}	1.2261	C_{66}	1.2334	C_{98}	-1.8151
C_3	-1.3981	C_{35}	1.4401	C_{67}	1.5338	C_{99}	-1.4829
C_4	0.8481	C_{36}	-0.5988	C_{68}	-0.8844	C_{100}	1.0302
C_5	1.0892	C_{37}	-0.4675	C_{69}	-0.3857	C_{101}	0.9419
C_6	-0.8621	C_{38}	0.8520	C_{70}	0.7730	C_{102}	-1.1472
C_7	1.1512	C_{39}	-0.8922	C_{71}	-0.9754	C_{103}	1.4858
C_8	0.9602	C_{40}	-0.5603	C_{72}	-0.2315	C_{104}	-0.6794
C_9	-1.3581	C_{41}	1.1886	C_{73}	0.5579	C_{105}	0.9573
C_{10}	-0.8354	C_{42}	1.1128	C_{74}	0.4035	C_{106}	1.0807
C_{11}	-1.3249	C_{43}	1.0833	C_{75}	0.4248	C_{107}	1.1445
C_{12}	1.0964	C_{44}	-0.9073	C_{76}	-0.3359	C_{108}	-1.2312
C_{13}	1.3334	C_{45}	-1.6227	C_{77}	-0.9914	C_{109}	-0.6643
C_{14}	-0.7378	C_{46}	1.0013	C_{78}	0.5975	C_{110}	0.3836
C_{15}	1.3565	C_{47}	-1.6067	C_{79}	-0.8408	C_{111}	-1.1482
C_{16}	0.9361	C_{48}	0.3360	C_{80}	0.3587	C_{112}	-0.0353
C_{17}	-0.8212	C_{49}	-1.3136	C_{81}	-0.9604	C_{113}	-0.6747
C_{18}	-0.2662	C_{50}	-1.4448	C_{82}	-1.0002	C_{114}	-1.1653
C_{19}	-0.6866	C_{51}	-1.7238	C_{83}	-1.1636	C_{115}	-0.8896
C_{20}	0.8437	C_{52}	1.0287	C_{84}	0.9590	C_{116}	0.2414
C_{21}	1.1237	C_{53}	0.6100	C_{85}	0.7137	C_{117}	0.1160
C_{22}	-0.3265	C_{54}	-0.9237	C_{86}	-0.6776	C_{118}	-0.6987
C_{23}	1.0511	C_{55}	1.2618	C_{87}	0.9824	C_{119}	0.4781
C_{24}	0.7927	C_{56}	0.5974	C_{88}	-0.5454	C_{120}	0.1821
C_{25}	-0.3363	C_{57}	-1.0976	C_{89}	1.1022	C_{121}	-1.0672
C_{26}	-0.1342	C_{58}	-0.9776	C_{90}	1.6485	C_{122}	-0.9676
C_{27}	-0.1546	C_{59}	-0.9982	C_{91}	1.3307	C_{123}	-1.2321
C_{28}	0.6955	C_{60}	0.8967	C_{92}	-1.2852	C_{124}	0.5003
C_{29}	1.0608	C_{61}	1.7640	C_{93}	-1.2659	C_{125}	0.7419
C_{30}	-0.1600	C_{62}	-1.0211	C_{94}	0.9435	C_{126}	-0.8934
C_{31}	0.9442	C_{63}	1.6913	C_{95}	-1.6809	C_{127}	0.8391

Table 6 – Time-domain packet synchronization sequence for Preamble Pattern 2

Sequence Element	Value	Sequence Element	Value	Sequence Element	Value	Sequence Element	Value
C_0	0.9679	C_{32}	-1.2905	C_{64}	1.5280	C_{96}	0.5193
C_1	-1.0186	C_{33}	1.1040	C_{65}	-0.9193	C_{97}	-0.3439
C_2	0.4883	C_{34}	-1.2408	C_{66}	1.1246	C_{98}	0.1428
C_3	0.5432	C_{35}	-0.8062	C_{67}	1.2622	C_{99}	0.6251
C_4	-1.4702	C_{36}	1.5425	C_{68}	-1.4406	C_{100}	-1.0468
C_5	-1.4507	C_{37}	1.0955	C_{69}	-1.4929	C_{101}	-0.5798
C_6	-1.1752	C_{38}	1.4284	C_{70}	-1.1508	C_{102}	-0.8237
C_7	-0.0730	C_{39}	-0.4593	C_{71}	0.4126	C_{103}	0.2667
C_8	-1.2445	C_{40}	-1.0408	C_{72}	-1.0462	C_{104}	-0.9563
C_9	0.3143	C_{41}	1.0542	C_{73}	0.7232	C_{105}	0.6016
C_{10}	-1.3951	C_{42}	-0.4446	C_{74}	-1.1574	C_{106}	-0.9964
C_{11}	-0.9694	C_{43}	-0.7929	C_{75}	-0.7102	C_{107}	-0.3541
C_{12}	0.4563	C_{44}	1.6733	C_{76}	0.8502	C_{108}	0.3965
C_{13}	0.3073	C_{45}	1.7568	C_{77}	0.6260	C_{109}	0.5201
C_{14}	0.6408	C_{46}	1.3273	C_{78}	0.9530	C_{110}	0.4733
C_{15}	-0.9798	C_{47}	-0.2465	C_{79}	-0.4971	C_{111}	-0.2362
C_{16}	-1.4116	C_{48}	1.6850	C_{80}	-0.8633	C_{112}	-0.6892
C_{17}	0.6038	C_{49}	-0.7091	C_{81}	0.6910	C_{113}	0.4787
C_{18}	-1.3860	C_{50}	1.1396	C_{82}	-0.3639	C_{114}	-0.2605
C_{19}	-1.0888	C_{51}	1.5114	C_{83}	-0.8874	C_{115}	-0.5887
C_{20}	1.1036	C_{52}	-1.4343	C_{84}	1.5311	C_{116}	0.9411
C_{21}	0.7067	C_{53}	-1.5005	C_{85}	1.1546	C_{117}	0.7364
C_{22}	1.1667	C_{54}	-1.2572	C_{86}	1.1935	C_{118}	0.6714
C_{23}	-1.0225	C_{55}	0.8274	C_{87}	-0.2930	C_{119}	-0.1746
C_{24}	-1.2471	C_{56}	-1.5140	C_{88}	1.3285	C_{120}	1.1776
C_{25}	0.7788	C_{57}	1.1421	C_{89}	-0.7231	C_{121}	-0.8803
C_{26}	-1.2716	C_{58}	-1.0135	C_{90}	1.2832	C_{122}	1.2542
C_{27}	-0.8745	C_{59}	-1.0657	C_{91}	0.7878	C_{123}	0.5111
C_{28}	1.2175	C_{60}	1.4073	C_{92}	-0.8095	C_{124}	-0.8209
C_{29}	0.8419	C_{61}	1.8196	C_{93}	-0.7463	C_{125}	-0.8975
C_{30}	1.2881	C_{62}	1.1679	C_{94}	-0.8973	C_{126}	-0.9091
C_{31}	-0.8210	C_{63}	-0.4131	C_{95}	0.5560	C_{127}	0.2562

Table 7 – Time-domain packet synchronization sequence for Preamble Pattern 3

Sequence Element	Value	Sequence Element	Value	Sequence Element	Value	Sequence Element	Value
C_{0}	0.4047	C_{32}	-0.9671	C_{64}	-0.7298	C_{96}	0.2424
C_{1}	0.5799	C_{33}	-0.9819	C_{65}	-0.9662	C_{97}	0.5703
C_{2}	-0.3407	C_{34}	0.7980	C_{66}	0.9694	C_{98}	-0.6381
C_{3}	0.4343	C_{35}	-0.8158	C_{67}	-0.8053	C_{99}	0.7861
C_{4}	0.0973	C_{36}	-0.9188	C_{68}	-0.9052	C_{100}	0.9175
C_{5}	-0.7637	C_{37}	1.5146	C_{69}	1.5933	C_{101}	-0.4595
C_{6}	-0.6181	C_{38}	0.8138	C_{70}	0.8418	C_{102}	-0.2201
C_{7}	-0.6539	C_{39}	1.3773	C_{71}	1.5363	C_{103}	-0.7755
C_{8}	0.3768	C_{40}	0.2108	C_{72}	0.3085	C_{104}	-0.2965
C_{9}	0.7241	C_{41}	0.9245	C_{73}	1.3016	C_{105}	-1.1220
C_{10}	-1.2095	C_{42}	-1.2138	C_{74}	-1.5546	C_{106}	1.7152
C_{11}	0.6027	C_{43}	1.1252	C_{75}	1.5347	C_{107}	-1.2756
C_{12}	0.4587	C_{44}	0.9663	C_{76}	1.0935	C_{108}	-0.7731
C_{13}	-1.3879	C_{45}	-0.8418	C_{77}	-0.8978	C_{109}	1.0724
C_{14}	-1.0592	C_{46}	-0.6811	C_{78}	-0.9712	C_{110}	1.1733
C_{15}	-1.4052	C_{47}	-1.3003	C_{79}	-1.3763	C_{111}	1.4711
C_{16}	-0.8439	C_{48}	-0.3397	C_{80}	-0.6360	C_{112}	0.4881
C_{17}	-1.5992	C_{49}	-1.1051	C_{81}	-1.2947	C_{113}	0.7528
C_{18}	1.1975	C_{50}	1.2400	C_{82}	1.6436	C_{114}	-0.6417
C_{19}	-1.9525	C_{51}	-1.3975	C_{83}	-1.6564	C_{115}	1.0363
C_{20}	-1.5141	C_{52}	-0.7467	C_{84}	-1.1981	C_{116}	0.8002
C_{21}	0.7219	C_{53}	0.2706	C_{85}	0.8719	C_{117}	-0.0077
C_{22}	0.6982	C_{54}	0.7294	C_{86}	0.9992	C_{118}	-0.2336
C_{23}	1.2924	C_{55}	0.7444	C_{87}	1.4872	C_{119}	-0.4653
C_{24}	-0.9460	C_{56}	-0.3970	C_{88}	-0.4586	C_{120}	0.6862
C_{25}	-1.2407	C_{57}	-1.0718	C_{89}	-0.8404	C_{121}	1.2716
C_{26}	0.4572	C_{58}	0.6646	C_{90}	0.6982	C_{122}	-0.8880
C_{27}	-1.2151	C_{59}	-1.1037	C_{91}	-0.7959	C_{123}	1.4011
C_{28}	-0.9869	C_{60}	-0.5716	C_{92}	-0.5692	C_{124}	0.9531
C_{29}	1.2792	C_{61}	0.9001	C_{93}	1.3528	C_{125}	-1.1210
C_{30}	0.6882	C_{62}	0.7317	C_{94}	0.9536	C_{126}	-0.9489
C_{31}	1.2586	C_{63}	0.9846	C_{95}	1.1784	C_{127}	-1.2566

Table 8 – Time-domain packet synchronization sequence for Preamble Pattern 4

Sequence Element	Value	Sequence Element	Value	Sequence Element	Value	Sequence Element	Value
C_0	1.1549	C_{32}	-1.2385	C_{64}	1.3095	C_{96}	-1.0094
C_1	1.0079	C_{33}	-0.7883	C_{65}	0.6675	C_{97}	-0.7598
C_2	0.7356	C_{34}	-0.7954	C_{66}	1.2587	C_{98}	-1.0786
C_3	-0.7434	C_{35}	1.0874	C_{67}	-0.9993	C_{99}	0.6699
C_4	-1.3930	C_{36}	1.1491	C_{68}	-1.0052	C_{100}	0.9813
C_5	1.2818	C_{37}	-1.4780	C_{69}	0.6601	C_{101}	-0.5563
C_6	-1.1033	C_{38}	0.8870	C_{70}	-1.0228	C_{102}	1.0548
C_7	-0.2523	C_{39}	0.4694	C_{71}	-0.7489	C_{103}	0.8925
C_8	-0.7905	C_{40}	1.5066	C_{72}	0.5086	C_{104}	-1.3656
C_9	-0.4261	C_{41}	1.1266	C_{73}	0.1563	C_{105}	-0.8472
C_{10}	-0.9390	C_{42}	0.9935	C_{74}	0.0673	C_{106}	-1.3110
C_{11}	0.4345	C_{43}	-1.2462	C_{75}	-0.8375	C_{107}	1.1897
C_{12}	0.4433	C_{44}	-1.7869	C_{76}	-1.0746	C_{108}	1.5127
C_{13}	-0.3076	C_{45}	1.7462	C_{77}	0.4454	C_{109}	-0.7474
C_{14}	0.5644	C_{46}	-1.4881	C_{78}	-0.7831	C_{110}	1.4678
C_{15}	0.2571	C_{47}	-0.4090	C_{79}	-0.3623	C_{111}	1.0295
C_{16}	-1.0030	C_{48}	-1.4694	C_{80}	-1.3658	C_{112}	-0.9210
C_{17}	-0.7820	C_{49}	-0.7923	C_{81}	-1.0854	C_{113}	-0.4784
C_{18}	-0.4064	C_{50}	-1.4607	C_{82}	-1.4923	C_{114}	-0.5022
C_{19}	0.9034	C_{51}	0.9113	C_{83}	0.4233	C_{115}	1.2153
C_{20}	1.5406	C_{52}	0.8454	C_{84}	0.6741	C_{116}	1.5783
C_{21}	-1.4613	C_{53}	-0.8866	C_{85}	-1.0157	C_{117}	-0.7718
C_{22}	1.2745	C_{54}	0.8852	C_{86}	0.8304	C_{118}	1.2384
C_{23}	0.3715	C_{55}	0.4918	C_{87}	0.4878	C_{119}	0.6695
C_{24}	1.8134	C_{56}	-0.6096	C_{88}	-1.4992	C_{120}	0.8821
C_{25}	0.9438	C_{57}	-0.4321	C_{89}	-1.1884	C_{121}	0.7807
C_{26}	1.3130	C_{58}	-0.1327	C_{90}	-1.4008	C_{122}	1.0537
C_{27}	-1.3070	C_{59}	0.4953	C_{91}	0.7795	C_{123}	-0.0791
C_{28}	-1.3462	C_{60}	0.9702	C_{92}	1.2926	C_{124}	-0.2845
C_{29}	1.6868	C_{61}	-0.8667	C_{93}	-1.2049	C_{125}	0.5790
C_{30}	-1.2153	C_{62}	0.6803	C_{94}	1.2934	C_{126}	-0.4664
C_{31}	-0.6778	C_{63}	-0.0244	C_{95}	0.8123	C_{127}	-0.1097

Table 9 – Frequency-domain OFDM training sequence

Tone Number	Value	Tone Number	Value	Tone Number	Value	Tone Number	Value
-56	$(1-j)/\sqrt{2}$	-28	$(1-j)/\sqrt{2}$	1	$(1+j)/\sqrt{2}$	29	$(1+j)/\sqrt{2}$
-55	$(-1+j)/\sqrt{2}$	-27	$(1-j)/\sqrt{2}$	2	$-(1+j)/\sqrt{2}$	30	$-(1+j)/\sqrt{2}$
-54	$(-1+j)/\sqrt{2}$	-26	$(-1+j)/\sqrt{2}$	3	$(1+j)/\sqrt{2}$	31	$-(1+j)/\sqrt{2}$
-53	$(1-j)/\sqrt{2}$	-25	$(-1+j)/\sqrt{2}$	4	$-(1+j)/\sqrt{2}$	32	$(1+j)/\sqrt{2}$
-52	$(1-j)/\sqrt{2}$	-24	$(-1+j)/\sqrt{2}$	5	$-(1+j)/\sqrt{2}$	33	$-(1+j)/\sqrt{2}$
-51	$(1-j)/\sqrt{2}$	-23	$(1-j)/\sqrt{2}$	6	$-(1+j)/\sqrt{2}$	34	$-(1+j)/\sqrt{2}$
-50	$(-1+j)/\sqrt{2}$	-22	$(-1+j)/\sqrt{2}$	7	$-(1+j)/\sqrt{2}$	35	$-(1+j)/\sqrt{2}$
-49	$(1-j)/\sqrt{2}$	-21	$(-1+j)/\sqrt{2}$	8	$-(1+j)/\sqrt{2}$	36	$(1+j)/\sqrt{2}$
-48	$(-1+j)/\sqrt{2}$	-20	$(1-j)/\sqrt{2}$	9	$(1+j)/\sqrt{2}$	37	$-(1+j)/\sqrt{2}$
-47	$(-1+j)/\sqrt{2}$	-19	$(-1+j)/\sqrt{2}$	10	$(1+j)/\sqrt{2}$	38	$(1+j)/\sqrt{2}$
-46	$(-1+j)/\sqrt{2}$	-18	$(-1+j)/\sqrt{2}$	11	$(1+j)/\sqrt{2}$	39	$-(1+j)/\sqrt{2}$
-45	$(1-j)/\sqrt{2}$	-17	$(-1+j)/\sqrt{2}$	12	$-(1+j)/\sqrt{2}$	40	$-(1+j)/\sqrt{2}$
-44	$(-1+j)/\sqrt{2}$	-16	$(-1+j)/\sqrt{2}$	13	$(1+j)/\sqrt{2}$	41	$-(1+j)/\sqrt{2}$
-43	$(-1+j)/\sqrt{2}$	-15	$(1-j)/\sqrt{2}$	14	$-(1+j)/\sqrt{2}$	42	$-(1+j)/\sqrt{2}$
-42	$(-1+j)/\sqrt{2}$	-14	$(-1+j)/\sqrt{2}$	15	$(1+j)/\sqrt{2}$	43	$-(1+j)/\sqrt{2}$
-41	$(-1+j)/\sqrt{2}$	-13	$(1-j)/\sqrt{2}$	16	$-(1+j)/\sqrt{2}$	44	$-(1+j)/\sqrt{2}$
-40	$(-1+j)/\sqrt{2}$	-12	$(-1+j)/\sqrt{2}$	17	$-(1+j)/\sqrt{2}$	45	$(1+j)/\sqrt{2}$
-39	$(-1+j)/\sqrt{2}$	-11	$(1-j)/\sqrt{2}$	18	$-(1+j)/\sqrt{2}$	46	$-(1+j)/\sqrt{2}$
-38	$(1-j)/\sqrt{2}$	-10	$(1-j)/\sqrt{2}$	19	$-(1+j)/\sqrt{2}$	47	$-(1+j)/\sqrt{2}$
-37	$(-1+j)/\sqrt{2}$	-9	$(1-j)/\sqrt{2}$	20	$(1+j)/\sqrt{2}$	48	$-(1+j)/\sqrt{2}$
-36	$(1-j)/\sqrt{2}$	-8	$(-1+j)/\sqrt{2}$	21	$-(1+j)/\sqrt{2}$	49	$(1+j)/\sqrt{2}$
-35	$(-1+j)/\sqrt{2}$	-7	$(-1+j)/\sqrt{2}$	22	$-(1+j)/\sqrt{2}$	50	$-(1+j)/\sqrt{2}$
-34	$(-1+j)/\sqrt{2}$	-6	$(-1+j)/\sqrt{2}$	23	$(1+j)/\sqrt{2}$	51	$(1+j)/\sqrt{2}$
-33	$(-1+j)/\sqrt{2}$	-5	$(-1+j)/\sqrt{2}$	24	$-(1+j)/\sqrt{2}$	52	$(1+j)/\sqrt{2}$
-32	$(1-j)/\sqrt{2}$	-4	$(-1+j)/\sqrt{2}$	25	$-(1+j)/\sqrt{2}$	53	$(1+j)/\sqrt{2}$
-31	$(-1+j)/\sqrt{2}$	-3	$(1-j)/\sqrt{2}$	26	$-(1+j)/\sqrt{2}$	54	$-(1+j)/\sqrt{2}$
-30	$(-1+j)/\sqrt{2}$	-2	$(-1+j)/\sqrt{2}$	27	$(1+j)/\sqrt{2}$	55	$-(1+j)/\sqrt{2}$
-29	$(1-j)/\sqrt{2}$	-1	$(1-j)/\sqrt{2}$	28	$(1+j)/\sqrt{2}$	56	$(1+j)/\sqrt{2}$

1.3.4 PLCP header

The OFDM training symbols shall be followed by the PHY header, which contains the BAND EXTENSION field, the RATE of the MAC frame body, the length of the frame payload (which does not include the FCS), and the seed identifier for the data scrambler. The BAND EXTENSION field specifies the mode of transmission for the frame payload. The RATE field conveys the information about the type of modulation, the coding rate, and the spreading factor used to transmit the MAC frame body.

The PLCP header field shall be composed of 28 bits, as illustrated in Figure 5. Bit 0 shall be reserved for future use. The next three bits 1 to 3 shall encode the BAND EXTENSION field. Bit 4 shall be reserved for future use. Bits 5–8 shall encode the RATE. Bit 9 shall be reserved for future use. Bits 10–21 shall encode the LENGTH field, with the least significant bit (LSB) being transmitted first. Bit 22 shall be reserved for future use. Bits 23–24 shall encode the initial state of the scrambler, which is used to synchronize the descrambler of the receiver. Bits 25–27 shall be reserved for future use.

	BAND EXTENSION (3 bits)				RATE (4 bits)					LENGTH (12 bits)													SCRAMBLER (2 bits)				
R	B1	B2	B3	R	R1	R2	R3	R4	R	LSB											MSB	R	S1	S2	R	R	R
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

R: Reserved

Transmit Order (from left to right)

Figure 5 – PLCP Header bit assignment

1.3.4.1 Band Extension field (BAND EXTENSION)

Depending on the mode of transmission for the frame payload, the bits B1–B3 shall be set according to the values in Table 10.

Table 10 – Band extension parameters

Mode	B1 – B3
1	001
2	010
Reserved	000, 011 – 111

1.3.4.2 Date rate (RATE)

Depending on the information data rate (RATE), the bits R1–R4 shall be set according to the values in Table 11.

Table 11 – Rate-dependent parameters

Rate (Mb/s)	R1 – R4
55	0000
80	0001
110	0010
160	0011
200	0100
320	0101
480	0110
Reserved	0111–1111

1.3.4.3 PLCP length field (LENGTH)

The PLCP Length field shall be an unsigned 12-bit integer that indicates the number of octets in the frame payload (which does not include the FCS, the tail bits, or the pad bits).

1.3.4.4 PLCP scrambler field (SCRAMBLER)

The bits S1–S2 shall be set according to the scrambler seed identifier value. This two-bit value corresponds to the seed value chosen for the data scrambler.

1.3.5 Header modulation

The PLCP header, MAC header, HCS, and tail bits shall be modulated using an information data rate of 55 Mb/s.

1.3.6 Optional band extension

If the frame payload is transmitted using Mode 2, then an optional band extension field will follow the PLCP header. The optional band extension field will not be used when the frame payload is transmitted using Mode 1.

The structure of the optional band extension for Mode 2 is shown in Figure 6. This field consists of scrambled pad bits spanning four OFDM symbols followed by 8 repetitions of the channel estimation sequence. The channel estimation sequence shall be constructed by passing the frequency-domain sequence, defined in Table 9, though the IFFT, and pre-appending the output with 32 “zero samples” and appending a guard interval consisting of 5 “zero samples” to the resulting time-domain output. This portion of the preamble can be used to estimate the channel frequency response for the upper four bands, for fine carrier frequency estimation, and fine symbol timing.

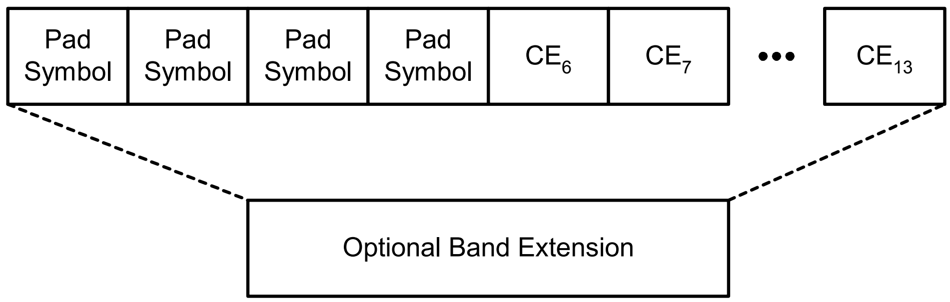


Figure 6 – Format for the optional band extension

1.3.7 Data scrambler

A side-stream scrambler shall be used for the MAC header, HCS, and MAC frame body. The PLCP preamble, PLCP header, and tail bits shall not be scrambled. The polynomial generator, $g(D)$, for the pseudo random binary sequence (PRBS) generator shall be $g(D) = 1 + D^{14} + D^{15}$, where D is a single bit delay element. The polynomial not only forms a maximal length sequence, but is also a primitive polynomial. Using this generator polynomial, the corresponding PRBS, x_n, is generated as

$$x_n = x_{n-14} \oplus x_{n-15}$$

where "⊕" denotes modulo-2 addition. The following sequence defines the initialization sequence, x_{init}, which is specified by the parameter "seed value" in Table 12.

$$x_{init} = [x_{n-1}^{i} \quad x_{n-2}^{i} \quad \cdots \quad x_{n-14}^{i} \quad x_{n-15}^{i}]$$

where x_{n-k}^{i} represents the binary initial value at the output of the kth delay element.

The scrambled data bits, s_n, are obtained as follows:

$$s_n = b_n \oplus x_n$$

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

The 15-bit seed value shall correspond to the seed identifier as shown in Table 12. The seed identifier value is set to 00 when the PHY is initialized and is incremented in a 2-bit rollover counter for each frame that is sent by the PHY. The value of the seed identifier that is used for the frame is sent in the PLCP header.

Table 12 – Scrambler seed selection

Seed identifier (b_1, b_0)	Seed value ($x_{14} \ldots x_0$)
0,0	0011 1111 1111 111
0,1	0111 1111 1111 111
1,0	1011 1111 1111 111
1,1	1111 1111 1111 111

1.3.8 Tail bits

The 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 the future bits when decoding the message stream. All tail bit fields (after the PHY header, after the HCS, and after the MAC frame payload) shall be produced by replacing the six scrambled bits with six “zero” bits.

1.3.9 Convolutional Encoder

The PLCP header, MAC header, and HCS shall be coded with a convolutional encoder of rate R = 11/32. The MAC frame body and tail bits shall be coded with a convolutional encoder of rate R = 11/32, 1/2, 5/8, or 3/4, corresponding to the desired data rate. The convolutional encoder shall use the rate R = 1/3 industry-standard generator polynomials, $g_0 = 133_8$, $g_1 = 145_8$, and $g_2 = 175_8$, as shown in Figure 7. The bit denoted as “A” shall be the first bit generated by the encoder, followed by the bit denoted as “B”, and finally, by the bit denoted as “C”. The various coding rates are derived from the rate R = 1/3 convolutional code by employing “puncturing”. Puncturing is a procedure for omitting some of the encoded bits in the transmitter (thus reducing the number of transmitted bits and increasing the coding rate) and inserting a dummy “zero” metric into the convolutional decoder on the receive side in place of the omitted bits. The puncturing patterns are illustrated in Figure 8 through Figure 11.

Decoding by the Viterbi algorithm is recommended.

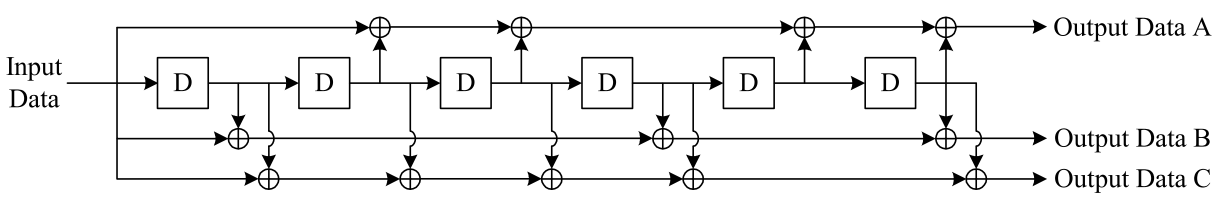


Figure 7 – Convolutional encoder: rate R = 1/3, constraint length K = 7

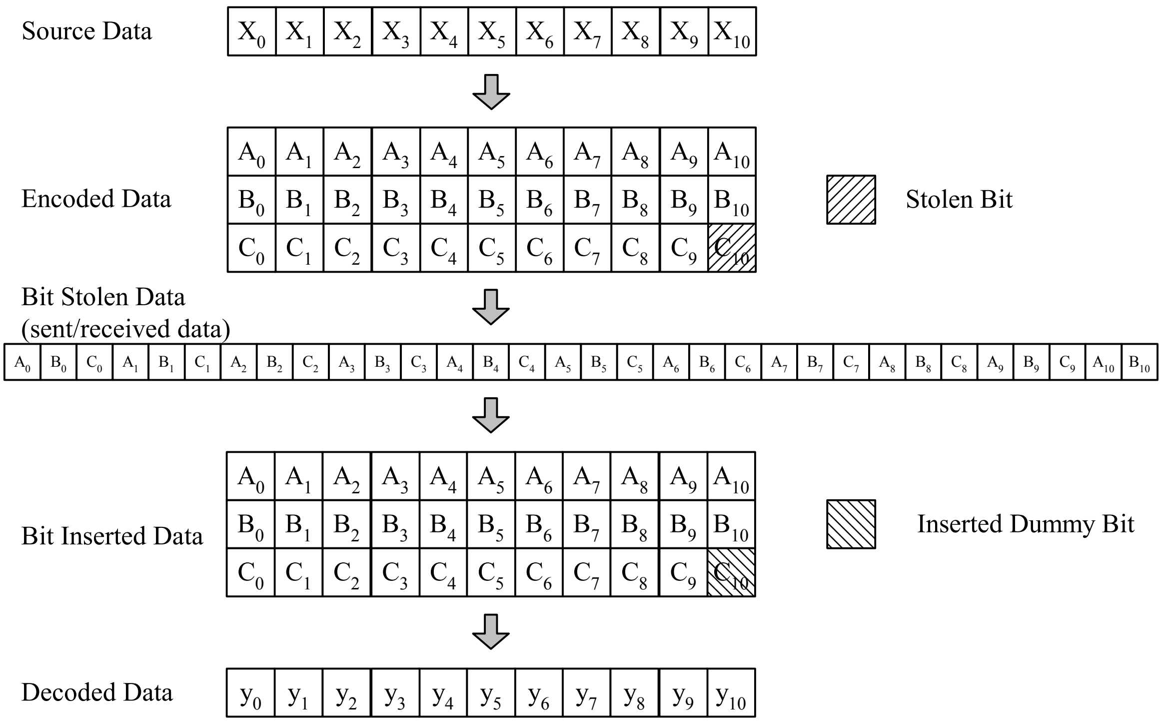


Figure 8 – An example of the bit-stealing and bit-insertion procedure (R = 11/32)

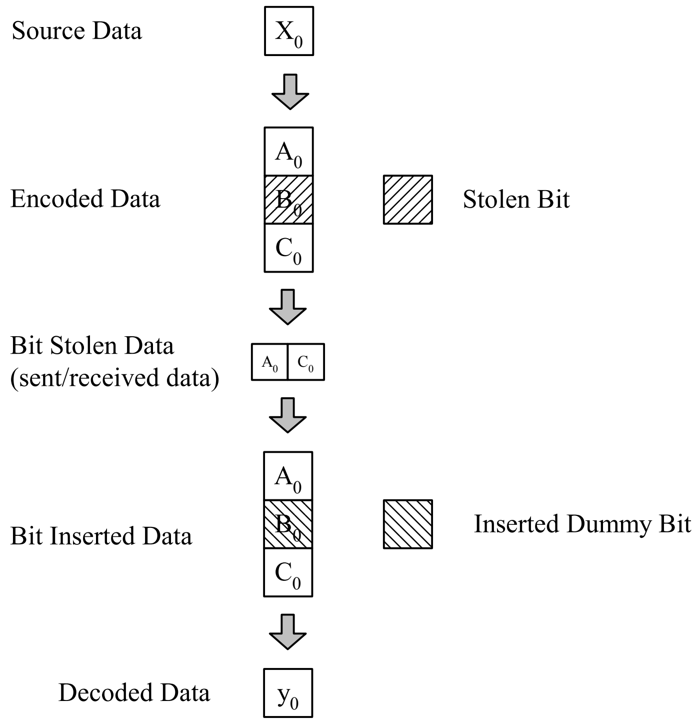


Figure 9 – An example of the bit-stealing and bit-insertion procedure (R = 1/2)

Figure 10 – An example of the bit-stealing and bit-insertion procedure (R = 5/8)

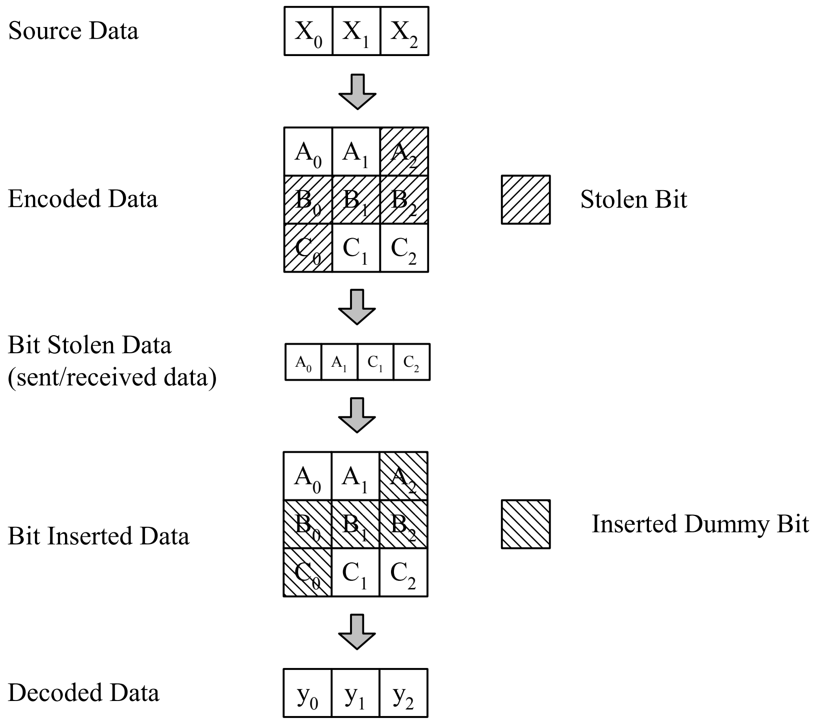


Figure 11– An example of the bit-stealing and bit-insertion procedure (R = 3/4)

1.3.10 Pad bits

The number of pad bits that are inserted is a function of the code rate R and the number of bits in the frame payload (LENGTH), FCS, and tail bits. Pad bits shall be inserted in order to ensure that there is alignment on the OFDM symbol boundaries. The number of OFDM symbols, N_{SYM}, is computed as follows:

$$N_{SYM} = \text{Ceiling}\,[\text{Ceiling}\,[1/R \times (8 \times (\text{LENGTH} + \text{FCS}) + 6)] / N_{CBPS}]$$

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.

1.3.11 Bit interleaving

The coded bit stream is interleaved prior to modulation. Bit interleaving provides robustness against burst errors. The bit interleaving operation is performed in two stages: symbol interleaving followed by tone interleaving. The symbol interleaver permutes the bits across OFDM symbols to exploit frequency diversity across the sub-bands, while the tone interleaver permutes the bits across the data tones within an OFDM symbol to exploit frequency diversity across tones and provide robustness against narrow-band interferers. We constrain our symbol interleaver to interleave among $3N_{CBPS}$ coded bits for Mode 1 devices and $7N_{CBPS}$ coded bits for Mode 2 devices, where N_{CBPS} is the number of coded bits per OFDM symbol.

The bit interleaving operation is described here for devices operating in Mode 1. First, the coded bits are grouped together into blocks of 3NCBPS coded bits, which corresponds to three OFDM symbols. Each group of coded bits is then permuted using a regular symbol block interleaver of size $N_{CBPS} \times 3$.Let the sequences $\{U(i)\}$ and $\{S(j)\}$, where i, $j = 0,\ldots, 3N_{CBPS}-1$, represent the input and output bits of the symbol block interleaver, respectively. The input-output relationship of this interleaver is given by:

$$S(j) = U\left\{\text{Floor}\left(\frac{i}{N_{CBPS}}\right) + 3\text{Mod}(i, N_{CBPS})\right\},$$

where the function Floor(·) returns the largest integer value less than or equal to its argument value and where the function Mod(·) returns the remainder after division of N_{CBPS} by i. If the coded bits available at the input of the symbol block interleaver correspond to less than $3N_{CBPS}$ coded bits, the output of the encoder is padded out to $3N_{CBPS}$ bits. Note that the pad bits are inserted at the input of the scrambler to ensure that the pad bits do not introduce any structure.

The output of the symbol block interleaver is then passed through a tone block interleaver. The outputs of the symbol block interleaver after grouped together into blocks of N_{CBPS} bits and then permuted using a regular block interleaver of size $N_{Tint} \times 10$, where $N_{Tint} = N_{CBPS}/10$. Let the sequences $\{S(i)\}$ and $\{V(j)\}$, where i, $j = 0,\ldots, N_{CBPS}-1$, represent the input and output bits of the tone interleaver, respectively. The input-output relationship of the tone block interleaver is given by:

$$T(j) = S\left\{\text{Floor}\left(\frac{i}{N_{T\text{int}}}\right) + 10\text{Mod}(i, N_{Tint})\right\},$$

where the function Mod(·) returns the remainder after division of N_{Tint} by i.

1.3.12 Subcarrier constellation mapping

The OFDM subcarriers shall be modulated using QPSK modulation. The encoded and interleaved binary serial input data shall be divided into groups of 2 bits and converted into complex numbers representing QPSK constellation points. The conversion shall be performed according to the Gray-coded constellation mappings, illustrated in Figure 12, with the input bit, b_0, being the earliest in the stream. The output values, d, are formed by multiplying the resulting (I + jQ) value by a normalization factor of K_{MOD}, as described in the following equation:

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

The normalization factor, KMOD, depends on the base modulation mode, as prescribed in Table 13. In practical implementations, an approximate value of the normalization factor can be used, as long as the device conforms to the modulation accuracy requirements.

For QPSK, b_0 determines the I value and b_1 determines the Q value, as illustrated in Table 14.

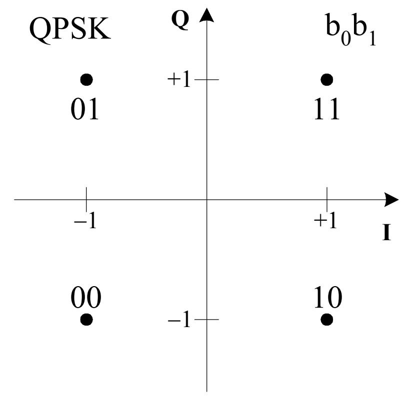


Figure 12 – QPSK constellation bit encoding

Table 13 – Modulation-dependent normalization factor K_{MOD}

Modulation	K_{MOD}
QPSK	$1/\sqrt{2}$

Table 14 – QPSK encoding table

Input bit (b_0 b_1)	I-out	Q-out
00	-1	-1
01	-1	1
10	1	-1
11	1	1

1.3.13 OFDM modulation

For information data rates of 50, and 80 Mb/s, the stream of complex numbers is divided into groups of 50 complex numbers. We shall denote these complex numbers $c_{n,k}$, which corresponds to subcarrier n of OFDM symbol k, as follows:

$$
\begin{aligned}
c_{n,k} &= d_{n+50\times k} \qquad\qquad n = 0,1,\ldots,49, k = 0,1,\ldots,\mathrm{N_{SYM}} - 1 \\
c_{(n+50),k} &= d^{*}_{(49-n)+50\times k}
\end{aligned}
$$

where N_{SYM} denotes the number of OFDM symbols in the MAC frame body, tail bits, and pad bits.

For information data rates of 110, 160, 200, 320 and 480 Mb/s, the stream of complex numbers is divided into groups of 100 complex numbers. We shall denote these complex numbers $c_{n,k}$, which corresponds to subcarrier n of OFDM symbol k, as follows:

$$c_{n,k} = d_{n+100\times k} \qquad n = 0,1,\ldots,99, k = 0,1,\ldots,\mathrm{N}_{\mathrm{SYM}} - 1$$

where $\mathrm{N}_{\mathrm{SYM}}$ denotes the number of OFDM symbols in the MAC frame body, tail bits, and pad bits.

An OFDM symbol $r_{data,k}(t)$ is defined as

$$r_{data,k}(t) = \sum_{n=0}^{N_{SD}} c_{n,k} \exp(j2\pi M(n)\Delta_F(t - T_{CP})) + p_{\mathrm{mod}(k,127)} \sum_{n=-N_{ST}/2}^{N_{ST}/2} P_n \exp(j2\pi n\Delta_F(t - T_{CP}))$$

where N_{SD} is the number of data subcarriers, N_{ST} is the number of total subcarriers, and the function *M(n)* defines a mapping from the indices 0 to 99 to the logical frequency offset indices –56 to 56, excluding the locations reserved for the pilot subcarriers, guard subcarriers and the DC subcarrier (as described below):

$$M(n) = \begin{cases} n-56 & n = 0 \\ n-55 & 1 \le n \le 9 \\ n-54 & 10 \le n \le 18 \\ n-53 & 19 \le n \le 27 \\ n-52 & 28 \le n \le 36 \\ n-51 & 37 \le n \le 45 \\ n-50 & 46 \le n \le 49 \\ n-49 & 50 \le n \le 53 \\ n-48 & 54 \le n \le 62 \\ n-47 & 63 \le n \le 71 \\ n-46 & 72 \le n \le 80 \\ n-45 & 81 \le n \le 89 \\ n-44 & 90 \le n \le 98 \\ n-43 & n = 99 \end{cases}$$

The subcarrier frequency allocation is shown in **Error! Reference source not found.**. To avoid difficulties in DAC and ADC offsets and carrier feed-through in the RF system, the subcarrier falling at DC (0^{th} subcarrier) is not used.

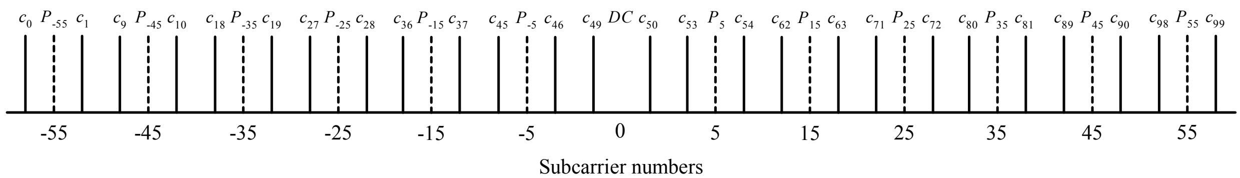


Figure 13 – Subcarrier frequency allocation

1.3.13.1 Pilot subcarriers

In each OFDM symbol, twelve of the subcarriers are dedicated to pilot signals in order to make coherent detection robust against frequency offsets and phase noise. These pilot signals shall be put in subcarriers –55, –45, –35, –25, –15 –5, 5, 15, 25, 35, 45, and 55. The pilot signals shall be BPSK modulated by a pseudo-random binary sequence, generated using a linear feedback shift register (LFSR), to prevent the generation of spectral lines. The contribution due to the pilot subcarriers for the k^{th} OFDM symbol is given by the inverse Fourier Transform of the sequence P_n:

$$P_n = \begin{cases} \dfrac{1+j}{\sqrt{2}} & n = 15,45 \\ \dfrac{-1+j}{\sqrt{2}} & n = -5,-25,-35,-45 \\ \dfrac{-1-j}{\sqrt{2}} & n = 5,25,35,55 \\ \dfrac{1-j}{\sqrt{2}} & n = -15,-45 \\ 0 & n = \pm1,\ldots,\pm4,\pm6,\ldots,\pm14,\pm16,\ldots,\pm24,\pm36,\ldots,\pm44,\pm46,\ldots,\pm54,\pm56 \end{cases}$$

The polarity of the pilot subcarriers is controlled by the following pseudo-random LFSR sequence, p_l:

$p_{0\ldots126}$ = {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, -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}.

Only one element of this sequence is used for an OFDM symbol.

1.3.13.2 Guard subcarriers

In each OFDM symbol ten subcarriers are dedicated to guard subcarriers or guard tones. The guard subcarriers can be used for various purposes, including relaxing the specs on transmit and receive filters.

The magnitude level of the guard tones is not specified other than the definition below, and implementations can use reduced power for these subcarriers if desired. The guard subcarriers shall be located in subcarriers –61, –60, …, –57, and 57, 58, …, 61. The same linear-feedback shift register (LFSR) sequence , p_l , that is used to scramble the pilot subcarriers is used to generate the modulating data for the guard subcarriers. The guard subcarrier symbol definition for the n^{th} subcarrier of the k^{th} symbol is given as follows:

$$P_{n,k} = p_{\mathrm{mod}(k+l,127)}\left(\frac{1+j}{\sqrt{2}}\right), \quad l = 0,1,2,3,4; \; n = -61+l$$

$$P_{n,k} = P^{*}_{-n,k}, \qquad n = 57,...,61$$

In this numbering, it is assumed that $k=0$ corresponds to the first channel estimation symbol CE0. The elements from the sequence , p_l,are selected independently for the pilots and the guard subcarriers in this section.

1.3.14 Time-domain Spreading

For data rates of 55, 80, 110, 160 and 200 Mbps a time-domain spreading operation is performed with a spreading factor of 2. The time-domain spreading operation consists of transmitting the same information over two OFDM symbols. These two OFDM symbols are transmitted over different sub-bands to obtain frequency diversity. For example, if the device uses a time-frequency code [1 2 3 1 2 3], as specified in Table 16, the information in the first OFDM symbol is repeated on sub-bands 1 and 2, the information in the second OFDM symbol is repeated on sub-bands 3 and 1, and the information in the third OFDM symbol is repeated on sub-bands 2 and 3.

1.4 General requirements

1.4.1 Operating band frequencies

1.4.1.1 Operating frequency range

This PHY operates in the 3.1 – 10.6 GHz frequency as regulated in the United States by the Code of Federal Regulations, Title 47, Section 15, as well as in any other areas that the regulatory bodies have also allocated this band.

1.4.1.2 Band numbering

The relationship between center frequency and band number is given by the following equation:

$$\text{Band center frequency} = \begin{cases} 2904 + 528 \times n_b & n_b = 1...4 \\ 3168 + 528 \times n_b & n_b = 5...13 \end{cases} \quad \text{(MHz)}.$$

This definition provides a unique numbering system for all channels that have a spacing of 528 MHz and lie within the band 3.1 – 10.6 GHz. In this proposal, bands 1 through 3 are used for Mode 1 devices (mandatory mode), while bands 1 through 3 and 6 through 9 are used for Mode 2 devices (optional mode). The remaining channels are reserved for future use. Table 15 summarizes the band allocation.

Table 15 – OFDM PHY band allocation

BAND_ID	Lower frequency	Center frequency	Upper frequency
1	3168 MHz	3432 MHz	3696 MHz
2	3696 MHz	3960 MHz	4224 MHz
3	4224 MHz	4488 MHz	4752 MHz
4	4752 MHz	5016 MHz	5280 MHz
5	5544 MHz	5808 MHz	6072 MHz
6	6072 MHz	6336 MHz	6600 MHz
7	6600 MHz	6864 MHz	7128 MHz
8	7128 MHz	7392 MHz	7656 MHz
9	7656 MHz	7920 MHz	8184 MHz
10	8184 MHz	8448 MHz	8712 MHz
11	8712 MHz	8976 MHz	9240 MHz
12	9240 MHz	9504 MHz	9768 MHz
13	9768 MHz	10032 MHz	10296 MHz

The frequency of operation for Mode 1 and Mode 2 devices is shown in Figure 14 and Figure 15, respectively.

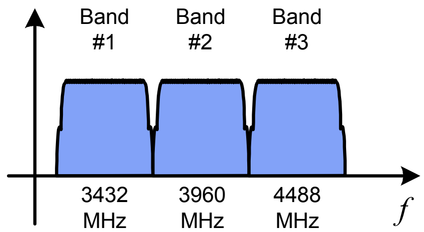


Figure 14 – Frequency of operation for a Mode 1 device.

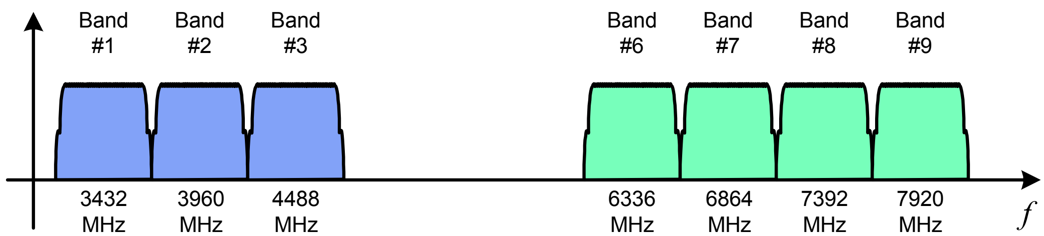


Figure 15 – Frequency of operation for a Mode 2 device.

1.4.2 Channelization

Channelization for different piconets is achieved by using different time-frequency codes for different piconets. In addition, different preamble patterns are used for the different piconets. Table 16 defines the time-frequency codes and preamble pattern for each piconet.

Table 16 – Time Frequency Codes and Preamble Patterns for Different Piconets

Channel Number	Preamble Pattern	Mode 1: Length 6 Time Frequency Code						Mode 2: Length 7 Time Frequency Code						
1	1	1	2	3	1	2	3	1	2	3	4	5	6	7
2	2	1	3	2	1	3	2	1	7	6	5	4	3	2
3	3	1	1	2	2	3	3	1	4	7	3	6	2	5
4	4	1	1	3	3	2	2	1	3	5	7	2	4	6

1.4.3 PHY layer timing

The values for the PHY layer timing parameters are defined in Table 17.

Table 17 – PHY layer timing parameters

PHY Parameter	Value
pMIFSTime	2 μs
pSIFSTime	10 μs
pCCADetectTime	4.6875 μs
pChannelSwitchTime	9.0 ns

1.4.3.1 Interframe spacing

A conformant implementation shall support the interframe spacing parameters given in Table 18.

Table 18 – Interframe spacing parameters

802.15.3 MAC Parameter	Corresponding PHY Parameter
MIFS	pMIFSTime
SIFS	pSIFSTime
pBackoffSlot	pSIFSTime + pCCADetectTime
BIFS	pSIFSTime + pCCADetectTime
RIFS	2*pSIFSTime + pCCADetectTime

1.4.3.2 Receive-to-transmit turnaround time

The RX-to-TX turnaround time shall be pSIFSTime. This turnaround time shall be measured at the air interface from the trailing edge of the last received OFDM symbol to the leading edge of the first transmitted OFDM symbol of the PLCP preamble for the next frame.

1.4.3.3 Transmit-to-receive turnaround time

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

1.4.3.4 Time between successive transmissions

The time between uninterrupted successive transmissions by the same DEV shall be pMIFSTime. This time shall be measured at the air interface from the trailing edge of the last OFDM symbol transmitted to the leading edge of the first OFDM symbol of the PLCP preamble for the following frame.

1.4.3.5 Channel switch time

The channel switch time is defined as the interval from when the trailing edge of the last valid OFDM symbol is on air until the PHY is ready to transmit or receive from the air another OFDM symbol on a new channel. The channel switch time shall not exceed pChannelSwitchTime.

1.4.4 Header check sequence

The combined PLCP and MAC headers shall be protected with a CCITT CRC-16 header check sequence (HCS). The PHY parameter, pLengthHCS shall be 2 for this PHY. The CCITT CRC-16 HCS shall be the ones complement of the remainder generated by the modulo-2 division of the protected combined PLCP and MAC headers by the polynomial: $x^{16} + x^{12} + x^5 + 1$. The protected bits shall be processed in the transmit order. All HCS calculations shall be made prior to data scrambling. A schematic of the processing order is shown in Figure 16.

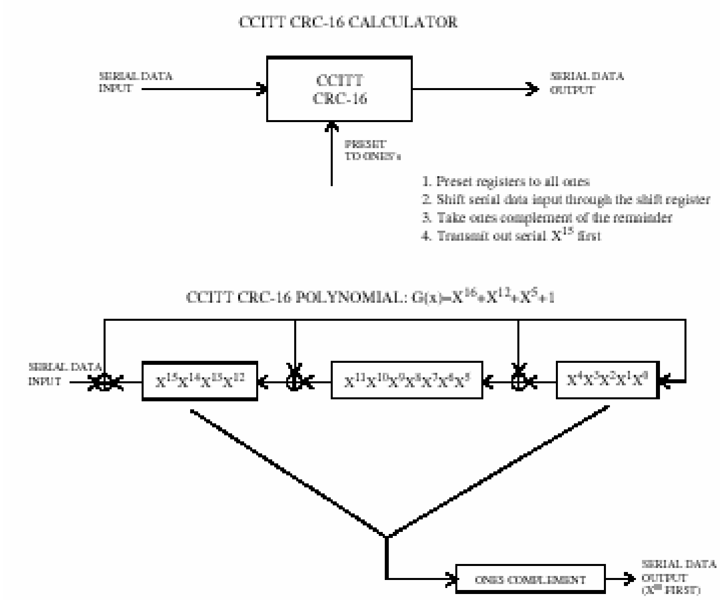


Figure 16 – CCITT CRC-16 Implementation

The CRC-16 described in this subclause is the same one used in the IEEE 802.15.3 draft standard.

1.5 Transmitter specifications

1.5.1 Transmit PSD mask

The transmitted spectrum shall have a 0 dBr (dB relative to the maximum spectral density of the signal) bandwidth not exceeding 260 MHz, –12 dBr at 285 MHz frequency offset, and –20 dBr at 330 MHz frequency offset and above. The transmitted spectral density of the transmitted signal mask shall fall within the spectral, as shown in Figure 17.

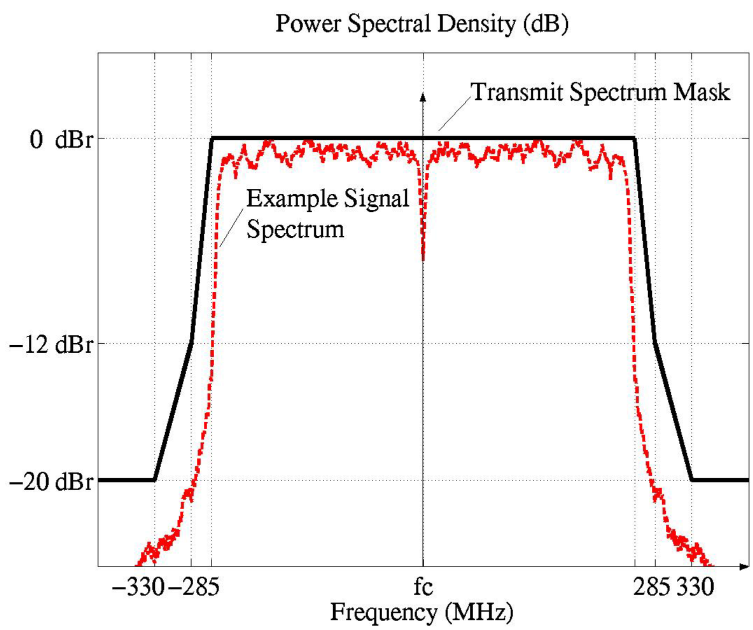


Figure 17 – Transmit Power Spectral Density Mask

1.5.2 Transmit center frequency tolerance

The transmitted center frequency tolerance shall be ±20 ppm maximum.

1.5.3 Symbol clock frequency tolerance

The symbol clock frequency tolerance shall be ±20 ppm maximum.

1.5.4 Clock synchronization

The transmit center frequency and the symbol clock frequency shall be derived from the same reference oscillator.

1.6 Receiver specification

1.6.1 Receiver sensitivity

For a packet error rate (PER) of less than 8% with a PSDU of 1024 bytes, the minimum receiver sensitivity numbers for the various rates and modes are listed in Table 19.

Table 19 – Receiver performance requirements

Data rate (Mb/s)	Minimum sensitivity (dBm) for Mode 1	Minimum sensitivity (dBm) for Mode 2
55	–83.5	–81.5
80	–81.7	–79.7
110	–80.5	–78.5
160	–78.7	–76.7
200	–77.2	–75.2
320	–75.1	–73.1
480	–72.7	–70.7

1.6.2 Receiver CCA performance

The start of a valid OFDM transmission at a receiver level equal to or greater than the minimum 55 Mb/s sensitivity (–83.5 dBm) shall cause CCA to indicate busy with a probability > 90% within 4.6875 µs. If the preamble portion was missed, the receiver shall hold the carrier sense (CS) signal busy for any signal 20 dB above the minimum 55 Mb/s sensitivity (–63.5 dBm).

2 Self evaluation matrix

2.1 General solution criteria

	REF.	*IMPORTANCE LEVEL*	*PROPOSER RESPONSE*
Unit Manufacturing Complexity (UMC)	3.1	B	+
Signal Robustness			
Interference And Susceptibility	3.2.2	A	+
Coexistence	3.2.3	A	+
Technical Feasibility			
Manufacturability	3.3.1	A	+
Time To Market	3.3.2	A	+
Regulatory Impact	3.3.3	A	+
Scalability (i.e. Payload Bit Rate/Data Throughput, Channelization – physical or coded, Complexity, Range, Frequencies of Operation, Bandwidth of Operation, Power Consumption)	3.4	A	+
Location Awareness	3.5	C	+

2.2 PHY protocol criteria

CRITERIA	*REF.*	*IMPORTANCE LEVEL*	*PROPOSER RESPONSE*
Size And Form Factor	5.1	B	+
PHY-SAP Payload Bit Rate & Data Throughput			
Payload Bit Rate	5.2.1	A	+
Packet Overhead	5.2.2	A	+
PHY-SAP Throughput	5.2.3	A	+
Simultaneously Operating Piconets	5.3	A	+
Signal Acquisition	5.4	A	+
System Performance	5.5	A	+
Link Budget	5.6	A	+
Sensitivity	5.7	A	+
Power Management Modes	5.8	B	+
Power Consumption	5.9	A	+
Antenna Practicality	5.10	B	+

2.3 MAC protocol enhancement criteria

CRITERIA	*REF.*	*IMPORTANCE LEVEL*	*PROPOSER RESPONSE*
MAC Enhancements And Modifications	4.1.	C	+

3 Detailed responses to selection criteria and self-evaluation matrix

3.1 Unit manufacturing cost

The total die size for the PHY solution is expected to be around 4.9 mm^2 for Mode 1 (3-band) devices, with 3.0 mm^2 for the analog/RF portion[1] and 1.9 mm^2 for the digital portion. These estimates assume a 90 nm CMOS technology node in 2004. If a 130 nm CMOS technology node is assumed, the total die size of the PHY solution for Mode 1 devices is expected to be around 7.1 mm^2, with 3.3 mm^2 for the analog/RF portion and 3.8 mm^2 for the digital potion. The digital portion of the PHY is expected to require 295K gates. The enhancements to the MAC are not expected to affect the die size or gate count of the MAC. The major external components that will be required by the complete solution (RF+PHY+MAC) are a pre-select filter, balun, crystal oscillator, voltage regulator, and SRAM for the MAC. For Mode 2 (7-band) devices, the analog portion of the die size is expected to increase to 2.4 mm^2 and 3.5 mm^2, respectively, for a 90 nm and 130 nm CMOS technology node.

3.2 Signal robustness

3.2.2 Interference and susceptibility

The receiver consists of a front-end pre-select filter to reject out-of band noise and interference. For the three-band Multi-band OFDM system (Mode 1) presented in this proposal, the pass-band of the pre-select filter is between 3168 MHz to 4752 MHz. The output of the pre-select filter is amplified using an LNA and is followed by down-conversion to the base-band using the appropriate center frequency. The base-band signal is filtered using a 3rd order low-pass filter. For Mode 2 devices, the pass-band of the pre-select filter also includes the band between 6076 MHz and 8184 MHz.

The interference and susceptibility analysis are presented for Mode 1 (3-band) devices that is assumed to be operating at 6 dB above the receiver sensitivity, namely P_d = –74.5 dBm (see **Error! Reference source not found.**), for an information data rate of 110 Mbps. Based on the link budget table of section **Error! Reference source not found.**, the average noise power per bit is –87 dBm. Since, a margin of 6 dB is available, the sum of the interferer-and-noise power can be at most –81 dBm to maintain a PER < 8% for a 1024 byte packet. Under the assumption that the impact of the interferer is similar to that of additive noise, this corresponds to a maximum tolerable interferer power of –82.3 dBm at the input of the decoder. The interference and susceptibility analysis for the following types of interferers has been provided in Table 20:

- Microwave oven
- IEEE 802.15.1 (Bluetooth)
- IEEE 802.11b

[1] Component area.

- IEEE 802.15.3
- IEEE 802.11a
- IEEE 802.15.4

Table 20 – Interference and Susceptibility Analysis

	Microwave Oven	Bluetooth & IEEE 802.15.1 Interferer	IEEE 802.11b & IEEE 802.15.3 Interferer	IEEE 802.11a Interferer	IEEE 802.15.4 Interferer (2.45 GHz)
Max. tolerable interferer power at the encoder	-82.3 dBm	-82.3 dBm	-82.3 dBm	-82.3 dBm	-82.3 dBm
Processing gain[2] (coding rate of 11/32)	4.6 dB	4.6 dB	4.6 dB	4.6 dB	4.6 dB
Minimum base-band filter attenuation	35.4 dB	36.9 dB	36.9 dB	30.7 dB	35.6 dB
Front-end pre-select filter attenuation	35 dB	35 dB	35 dB	30 dB	35 dB
Max. tolerable interferer power at the antenna	-7.3 dB	-5.8 dB	-5.8 dB	-17 dB	-7.1 dB
Interferer power at 1m separation	-23.2 dBm	-40 dBm	-20 dBm	-31.9 dBm	-40.2 dBm
Minimum margin	15.9 dB	34.2 dB	14.2 dB	14.1 dB	33.1 dB
Tolerable separation	≅ 0.16 m	≅ 0.02 m	≅ 0.2 m	≅ 0.2 m	≅ 0.02 m

3.2.2.1 Microwave oven

The microwave oven is an out-of-band interferer and based on the analysis presented in Table 20, the Multi-band OFDM system can tolerate this interferer at a minimum separation of 0.16 m.

3.2.2.2 Bluetooth and IEEE 802.15.1 interferer

This is an out-of-band interferer and based on the analysis presented in Table 20, the Multi-band OFDM system can tolerate this interferer at a minimum separation of 0.02 m.

3.2.2.3 IEEE 802.11b and IEEE 802.15.3 interferer

This is an out-of-band interferer and based on the analysis presented in Table 20, the Multi-band OFDM system can tolerate this interferer at a minimum separation of 0.2 m. This interference tolerance is

[2] This is a pessimistic analysis performed for the sub-band closest to the interferer and does not include the processing gain of $10\log_{10}(3)$ dB that arises from the use of Time-Frequency Codes across the 3 bands.

superior to the desired criteria of 0.3 m separation between the IEEE 802.11b interferer and the UWB reference device.

3.2.2.4 IEEE 802.11a interferer

As the Multi-band OFDM system only utilizes the spectrum between 3168 MHz and 4752 MHz, the IEEE 802.11a interferer is an out-of-band interferer. Hence, it is easier to design the front-end pre-select filter to reject the 802.11a interference. Based on the analysis presented in Table 20, the Multi-band OFDM system can tolerate this interferer at a minimum separation of at least 0.2 m. This interference tolerance is superior to the desired criteria of 0.3 m separation between the IEEE 802.11a interferer and the UWB reference device.

3.2.2.5 IEEE 802.15.4 interferer

This is an out-of-band interferer and the Multi-band OFDM system can tolerate this interferer at a minimum separation of 0.02 m. The analysis presented in Table 20 is only for the IEEE 802.15.4 interferer centered around 2.45 GHz. Although, the 802.15.4 device centered around 868 MHz and 915 MHz can have a receive power that is approximately 9 dB higher than that of the 802.15.4 device centered around 2.45 GHz, the base-band filter attenuation for these frequencies is significantly higher, and hence the 802.15.4 device with a center frequency of 2.45 GHz is the worst-case interferer.

3.2.2.6 Generic in-band modulated interferer

The robustness of the Multi-band OFDM system to the presence of a generic in-band modulated interferer was evaluated for Mode 1 (3-band) devices based on AWGN simulations that incorporate losses due to front-end filtering, clipping at the DAC, ADC degradation (4-bits for 110/200 Mbps), packet acquisition, channel estimation, clock frequency mismatch (± 20 ppm at the TX and RX), carrier offset recovery, carrier tracking, etc. The center frequency of the interferer was swept uniformly from 3254 MHz to 4704 MHz in uniform steps of 50 MHz. Since the symbol rate of the modulated interferer is only 5 MHz, it will interfere with only a couple of tones. The affected tones can be erased to combat the narrow-band interferer and erasure of these tones results in some performance degradation. One of the advantages of the Multi-band OFDM system is that the sub-band in which the narrow band interferer is present can still be used with minimal impact. When operating at 6 dB above sensitivity for the 110 Mbps data rates, it was observed that the Multi-band OFDM system can tolerate a generic in-band modulated interferer with a power of $P_I > P_d - 9.0$ dB. The packet error rate performance of the Multi-band OFDM system in the presence of an in-band modulated interferer is illustrated in Figure 18.

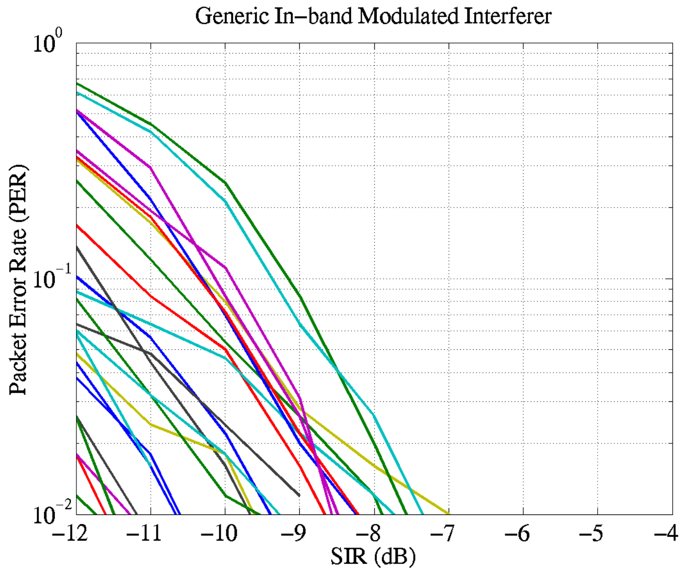


Figure 18: PER performance in the presence of a generic in-band modulated interferer

3.2.2.7 Generic in-band tone interferer

The robustness of the Multi-band OFDM system to the presence of a generic in-band tone interferer was evaluated for Mode 1 (3-band) devices based on AWGN simulations that incorporate losses due to front-end filtering, clipping at the DAC, ADC degradation (4-bits for 110/200 Mbps), packet acquisition, channel estimation, clock frequency mismatch (± 20 ppm at the TX and RX), carrier offset recovery, carrier tracking, etc. A generic in-band tone interferer will affect at most two tones in any OFDM symbol. The affected tones can be erased to combat the narrow-band interferer and erasure of these tones results in some performance degradation. Hence, the sub-band in which the narrow band interferer is present can still be used with minimal impact. When operating at 6 dB above sensitivity, for the 110 Mbps data rates, it was observed that the Multi-band OFDM system can tolerate a generic in-band tone interferer with a power of $P_I > P_d$ –8.0 dB. The packet error rate performance of the Multi-band OFDM system in the presence of an in-band modulated interferer is illustrated in Figure 19.

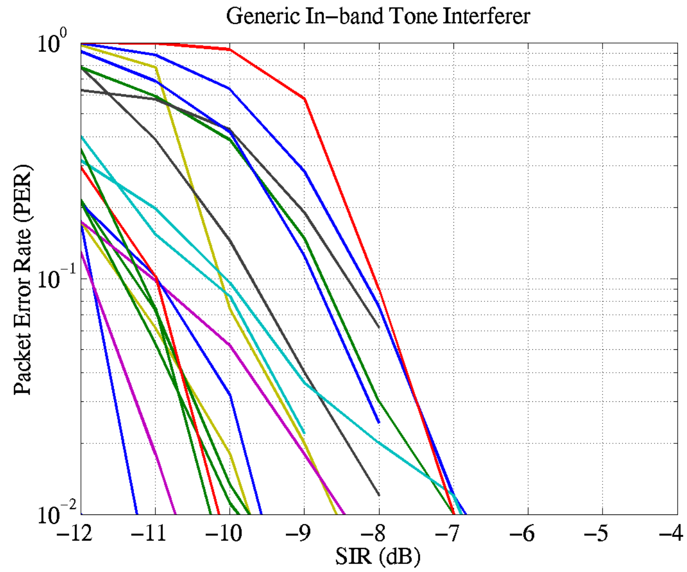


Figure 19: PER performance in the presence of a generic in-band tone interferer

3.2.2.8 Out-of-band interference from intentional and unintentional radiators

The minimum out-of-band rejection (in dB) provided by the Multi-band OFDM is listed in Table 21 for various center frequencies for Mode 1 (3-band) devices.

Table 21 – Minimum out-of-band rejection for Multi-band OFDM

Center Frequency	Pre-select Filter Attenuation	Base-band Filter Attenuation	Total Attenuation
900 MHz	35 dB	60 dB	95 dB
1900 MHz	35 dB	47 dB	82 dB
2450 MHz	35 dB	35 dB	70 dB
5150 MHz	25 dB	25 dB	50 dB
5300 MHz	30 dB	30 dB	60 dB
5850 MHz	35 dB	44 dB	79 dB

3.2.3 Coexistence

The Multi-band OFDM system is very coexistence friendly. Firstly, for the proposed system employing three sub-bands, all the victim receivers specified in the selection criteria document are essentially out-of-band. Hence, the impact of the Multi-band OFDM system on these devices will be minimal, if any. Secondly, the Multi-band OFDM system offers an enhanced level of co-existence with both existing and future narrow-band systems that occupy the same spectrum. Co-existence with in-band systems can be achieved by dynamically turning ON/OFF tones.

In this sub-section, out-of-band mask requirements on the Multi-band OFDM system will be computed based on the IEEE 802.11a and IEEE 802.11b victim receivers.

3.2.3.1 IEEE 802.11a interferer

The IEEE 802.11a receiver has a minimum receiver sensitivity of –82 dBm and a signal bandwidth of 20 MHz. For the average interfering power of the UWB device to be at least 6 dB less than the minimum sensitivity level of the victim receiver, at a distance separation of 0.3 m, the transmit power of the UWB device in the bandwidth of interest should be less than –51.5 dBm or equivalently –64.5 dBm/MHz. This corresponds to an out-of-band rejection mask of at least 23 dB at a frequency of 5.3 GHz. This level of out-of-band rejection can be easily achieved at the transmitter by using the front-end pre-select filter

3.2.3.2 IEEE 802.11b interferer

The IEEE 802.11b receiver has a minimum receiver sensitivity of –76 dBm and a signal bandwidth of 11 MHz. For the average interfering power of the UWB device to be at least 6 dB less than the minimum sensitivity level of the victim receiver, at a distance separation of 0.3 m, the transmit power of the UWB device in the bandwidth of interest should be less than –52.4 dBm or equivalently –62.8 dBm/MHz. This corresponds to an out-of-band rejection mask of at least 22 dB at a frequency of 2.4 GHz. This level of out-of-band rejection can be easily achieved at the transmitter by using the front-end pre-select filter.

3.3 Technical feasibility

3.3.1 Manufacturability

The proposed UWB solution will leverage current standard CMOS technology. Leveraging the standard analog and digital CMOS technology will result in a straightforward development effort. In addition, the digital section of the proposed PHY is similar to that of conventional and mature OFDM solutions, such as 802.11a and 802.11g.

3.3.2 Time to market

The earliest a complete CMOS PHY solution would be ready for integration is by the first half of 2005.

3.3.3 Regulatory impact

The proposed PHY complies the rules specified in the United States Code of Federal Regulations, Title 47, Section 15, Parts 15.517, 15.519, and 15.521 The proposed scheme will also comply in regions where they adopt the ruling specified by the FCC. Currently, there are no standardized regulations for UWB technologies in Europe, Japan, and Korea. However, regulatory efforts are underway in these regions. Due to the flexibility of the proposed scheme, it will comply with most regulatory standards.

3.4 Scalability

The proposed system demonstrates scalability of the following parameters:

1. *Power Consumption:* The power consumption scales monotonically with information data rate. The power consumption values are listed as a function of the information data rates in Table 36 and Table 37. Power consumption can be further reduced by using a half-rate PRF mode.

2. *Payload Bit Rate and Throughput:* Several payload bit rates have been specified for the Multi-band OFDM system in Table 3. Additional payload bit rates can be incorporated in the proposed system by defining new spreading/coding rates. New coding rates can be obtained by puncturing the rate 1/3 mother code and defining new puncturing patterns.

3. *Channelization:* Thirteen non-overlapping physical bands have been defined for the Multi-band OFDM system in Table 15. The first three bands will be used for Mode 1 devices (mandatory mode), while bands 1–3, 6–9 will be used for Mode 2 devices (optional mode). The remaining bands will be used as RF technology improves.

4. *Complexity:* The system complexity monotonically scales with the information data rate. Lower complexity devices are feasible by trading performance for implementation complexity.

5. *Range:* The range of the Multi-band OFDM system is a function of the data rate of operation and is tabulated in **Error! Reference source not found.** for the information data rates of 110 Mb/s, 200 Mb/s and 480 Mb/s.

6. *Frequencies of operation:* The proposed system can easily scale the frequencies of operation by adding or turning off some of the sub-bands.

7. *Occupied bandwidth:* The occupied bandwidth of the proposed system can be easily modified by dynamically turning on/off tones.

8. *Technology:* The Multi-band OFDM system has a comparable complexity between the analog and digital sections. The die size, power consumption and speed of operation of the digital section will scale with technology (Moore's law).

3.5 Location awareness

The Multi-band OFDM system has the capability to determine the relative location of one device with respect to another. The relative location information can be obtained by estimating the round trip delay between the devices. The total bandwidth of a Mode 1 Multi-band OFDM system is 1584 MHz, thus the accuracy that can be obtained for the location awareness is at least 10 cm. Greater accuracy can be obtained by using longer integration times. It may be possible to improve the accuracy to a few centimeters using this technique. A positioning protocol supports a time reference exchange between devices.

4 Alternate PHY required MAC enhancements and modifications

4.1 Introduction

This clause specifies the enhancements to the MAC that are needed in support of the proposed PHY.

The PHY specification defines certain time frequency codes (TFC) each of which is a repetition of an ordered group of channel indexes (see **Error! Reference source not found.**). Each TFC is designated by a unique TFC number. Given an TFC, the OFDM symbols of a PLCP frame, which starts with a PLCP preamble, are transmitted successively on each of the ordered channels, beginning from the first one, as defined for that HS.

A predetermined TFC, as specified by the PHY, is used in transmitting each beacon frame. This facilitates the reception of beacon frames by DEVs, and hence the synchronization of unassociated DEVs, or resynchronization of associated DEVs that have lost the synchronization, with a given PNC.

The MAC enhancements presented in this document specify the mechanisms that enable the MAC entity of any DEV in a given piconet to choose the appropriate time frequency code for its non-beacon frame transmissions, and to communicate the chosen time frequency code to the PHY entity within the same DEV.

4.2 Frame format enhancement for time-frequency coding

4.2.1 Time-frequency coding information element

The time-frequency code (TFC) IE contains a set of parameters necessary to allow synchronization for DEVs using the proposed PHY. The IE Payload field contains Time frequency code (TFC) parameter (see Figure 20).

Octets: 1	1	1
Element ID	Length	Time frequency code

Figure 20 – Time-Frequency Frequency information element (TFC IE) format

The Time frequency code field is 1 octet in length and specifies the current time frequency code (PHYPIB_CurrentTFC) of channel indexes within a set of time frequency codes.

Other fields may be added to this IE Payload in future MAC enhancements.

4.2.2 Piconet parameter change information element

4.2.3 Beacon frame

A TFC IE shall be included in each beacon frame of a piconet using the proposed PHY. It shall immediately follow the CTA IE(s) in the beacon.

4.3 Management enhancements for time-frequency coding

4.3.1 TFC PHY PIB

The following is added to the table for TFC PHY attributes.

Table 1 — FH PHY attributes (new)

Attribute	Length	Definition	Type
PHYPIB_CurrentTFC	1 octet	The time frequency code to be used by this DEV	Dynamic

The values of these attributes are updated by means of the PLME-SET.request and PLME-SET.confirm primitives as defined in Clause 6 of IEEE 802.15.3-2003 standard.

The PLME-SET.request contains two parameters, PHYPIB_Attribute and PHYPIB_Value, and is issued by the MLME to the PLME to set PHYPIB_Attribute to PHYPIB_Value. For the above attribute, this primitive is issued upon receiving a valid beacon or missing an expected beacon.

The PLME-SET.confirm contains two parameters, ResultCode and PHYPIB_Attribute, and is issued by the PLME to the MLME in response to a PLME-SET.request. The ResultCode indicates the result of setting the PHYPIB_Attribute to the requested value.

5 PHY layer criteria

5.1 Size and form factor

Solutions for the PC card, compact flash, memory stick, and SD memory will be available in 2005.

5.2 PHY-SAY payload bit rate and data throughput

5.2.1 Payload bit rate

The proposed UWB PHY supports information data rates of 55, 80, 110, 200, 320, and 480 Mb/s. The support of transmitting and receiving data rates of 55, 110, and 200 Mb/s are mandatory. The support for the remaining data rates of 80, 160, 320, and 480 Mb/s are optional.

5.2.2 Packet overhead for a Mode 1 device

The initial preamble is comprised of 30 OFDM symbols, where the duration of each OFDM symbol is 312.5 ns. Thus, the initial preamble has a length of 9.375 μs. Note that this value is independent of information data rate. The PLCP header, MAC header, HCS, and tail bits corresponds to 120 information bits. After encoding and puncturing, this corresponds to exactly 350 coded bits. Since, the PLCP header, MAC header, HCS, and tail bits are sent at an information data rate of 55 Mbps, these coded bits correspond to 8 OFDM symbols. Thus, the PLCP header, MAC header, HCS, and tail bits have a total length of 2.5 μs. Again, this time is independent of information data rate since it is always encoded at 55 Mbps.

Since the MPDU will be encoded at the information data rate, the length in time for the MPDU will vary according to the data rate. Using the equation defined in Section 1.3.10, we can determine the number of OFDM symbols that will be needed to transmit an MPDU+FCS of 1024 octets. Since the time for each OFDM symbol is 312.5 ns, we can easily determine the time required for 1024 octet data packets.

Table 22 summarizes the length in time for each component of the packet as a function of information data rate.

Table 22 – Time duration of each component of the packet versus data rate

Time	Length at 55 Mb/s	Length at 80 Mb/s	Length at 110 Mb/s	Length at 160 Mb/s	Length at 200 Mb/s	Length at 320 Mb/s	Length at 480 Mb/s
T_PA_INIT	9.375 µs	9.375 µs	9.375 µs	9.375 µs	9.375 µs	9.375 µs	9.375 µs
T_PHYHDR + T_MACHDR + T_HCS + T_TAILBITS	2.5 µs	2.5 µs	2.5 µs	2.5 µs	2.5 µs	2.5 µs	2.5 µs
T_DATA	149.0625 µs	102.5 µs	74.6875 µs	51.25 µs	41.25 µs	25.625 µs	17.1875 µs
T_MIFS	2 µs	2 µs	2 µs	2 µs	2 µs	2 µs	2 µs
T_PA_CONT	4.6875 µs	4.6875 µs	4.6875 µs	4.6875 µs	4.6875 µs	4.6875 µs	4.6875 µs
T_SIFS	10 µs	10 µs	10 µs	10 µs	10 µs	10 µs	10 µs
T_RIFS	24.6875 µs	24.6875 µs	24.6875 µs	24.6875 µs	24.6875 µs	24.6875 µs	24.6875 µs
T_BIFS	14.6875 µs	14.6875 µs	14.6875 µs	14.6875 µs	14.6875 µs	14.6875 µs	14.6875 µs

5.2.3 PHY-SAP throughput for a Mode 1 device

The throughput for a single frame and multiple frame (5 frames) transmission with an MPDU of 1024 bytes as a function of the information data rate is summarized in Table 23.

Table 23 – Throughput for a 1024 byte MPDU versus data rate (single/multiple frames)

# of frames	Throughput at 55 Mb/s	Throughput at 80 Mbps	Throughput at 110 Mbps	Throughput at 160 Mbps	Throughput at 200 Mbps	Throughput at 320 Mbps	Throughput at 480 Mbps
1	47.92 Mb/s	65.87 Mb/s	84.84 Mb/s	112.03 Mb/s	129.77 Mb/s	172.46 Mb/s	209.66 Mb/s
5	50.95 Mb/s	71.72 Mb/s	94.80 Mb/s	130.08 Mb/s	154.64 Mb/s	219.33 Mb/s	283.24 Mb/s

The throughput for a single frame and multiple frame (5 frames) transmission with an MPDU of 4024 bytes as a function of the information data rate is summarized in Table 24.

Table 24 – Throughput for a 4024 byte MPDU versus data rate (single/multiple frames)

# of frames	Throughput at 55 Mb/s	Throughput at 80 Mbps	Throughput at 110 Mbps	Throughput at 160 Mbps	Throughput at 200 Mbps	Throughput at 320 Mbps	Throughput at 480 Mbps
1	52.94 Mb/s	75.79 Mb/s	102.20 Mb/s	144.14 Mb/s	175.63 Mb/s	262.54 Mb/s	361.12 Mb/s
5	53.84 Mb/s	77.64 Mb/s	105.60 Mb/s	151.01 Mb/s	185.93 Mb/s	286.27 Mb/s	407.57 Mb/s

5.3 Simultaneously operating piconets

The simultaneously operating piconet performance of the Multi-band OFDM system was evaluated, based on simulations, in the presence of un-coordinated piconets. The performance simulations incorporate losses due to front-end filtering, clipping at the DAC, ADC degradation (4-bits for 110 Mbps), multi-path, packet acquisition, channel estimation, clock frequency mismatch (± 20 ppm at the TX and RX), carrier offset recovery, carrier tracking, etc. As specified in the test, the shadowing component was removed from both the reference and interfering links by normalizing each channel realization to unity multi-path energy. Table 25 lists the channel realizations used for the reference link and the interfering link as a function of the channel environment.

Table 25 – Channel realizations used in the simultaneously operating piconet test

Channel Environment	Reference Link	1st Piconet	2nd Piconet	3rd Piconet
CM1	1 to 5	6 to 10	99	100
CM2	1 to 5	6 to 10	99	100
CM3	1 to 5	6 to 10	99	100
CM4	1 to 5	6 to 10	99	100

Different time-frequency codes are assigned to the various simultaneously operating piconets. The time-frequency codes are designed to have good collision properties for all possible asynchronous shifts among the simultaneously operating piconets. The time-frequency codes used for this test are tabulated in Table 26 for both Mode 1 (3-band) and Mode 2 (7-band) devices.

Table 26 – Time-frequency codes for different piconets.

Channel Number	Time Frequency Codes (Mode 1)						Time Frequency Codes (Mode 2)						
1	1	2	3	1	2	3	1	2	3	4	5	6	7
2	1	3	2	1	3	2	1	7	6	5	4	3	2
3	1	1	2	2	3	3	1	4	7	3	6	2	5
4	1	1	3	3	2	2	1	3	5	7	2	4	6
5	-	-	-	-	-	-	1	5	2	6	3	7	4
6	-	-	-	-	-	-	1	6	4	2	7	5	3

To evaluate the simultaneously operating piconet performance, the test link is established such that the reference link is set at a distance of d_{ref} = 0.707 of the 90% link success probability distance. The distance separation at which a interfering piconets can be tolerated is obtained by averaging the performance over all combinations of the reference link and interferer link channel realizations for each channel environment. The d_{int}/d_{ref} values are tabulated in Table 27 for Mode 1 devices as a function of the multi-path channel environments the number of interfering piconets.

Table 27 – SOP Performance of Mode 1 (3-band) devices at a data rate of 110 Mbps.

Channel Environment	1 Int. Piconet	2 Int. Piconets*	3 Int. Piconets*
CM1 (d_{int}/d_{ref})	0.40	1.18	1.45

CM2 (d_{int}/d_{ref})	0.40	1.24	1.47
CM3 (d_{int}/d_{ref})	0.40	1.21	1.46
CM4 (d_{int}/d_{ref})	0.40	1.53	1.85

* Numbers based on July simulation results. We are currently, running simulations to update the improved SOP numbers.

Enhanced SOP performance can be achieved by the use of Mode 2 (7-band) devices and the d_{int}/d_{ref} values for these devices are tabulated for a data rate of 110 Mbps in Table 28 as a function of channel environment and the number of interfering piconets. Furthermore, the SOP performance results of Mode 2 devices, for a data rate of 200 Mbps, are tabulated in Table 29.

Table 28 – SOP Performance of Mode 2 (7-band) devices at a data rate of 110 Mbps.

Channel Environment	**1 Int. Piconet**	**2 Int. Piconets***	**3 Int. Piconets***
CM1 (d_{int}/d_{ref})	0.30	0.65	0.86
CM2 (d_{int}/d_{ref})	0.30	0.64	0.80
CM3 (d_{int}/d_{ref})	0.30	0.66	0.81
CM4 (d_{int}/d_{ref})	0.30	0.84	1.01

Table 29 – SOP Performance of Mode 2 (7-band) devices at a data rate of 200 Mbps.

Channel Environment	**1 Int. Piconet**	**2 Int. Piconets***	**3 Int. Piconets***
CM1 (d_{int}/d_{ref})	0.30	1.25	1.6
CM2 (d_{int}/d_{ref})	0.30	1.15	1.45
CM3 (d_{int}/d_{ref})	0.30	1.13	1.39
CM4 (d_{int}/d_{ref})	0.30	1.62	1.97

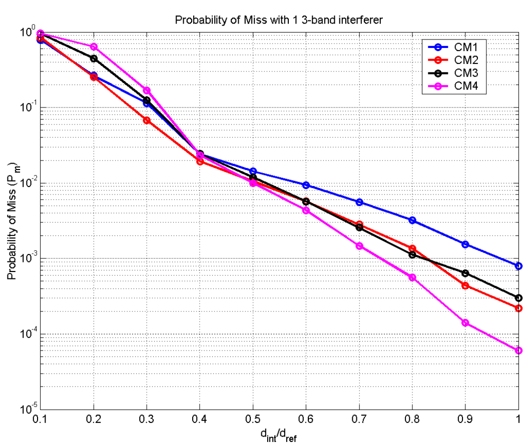
* Numbers based on July simulation results. We are currently running simulations to update the improved SOP numbers.

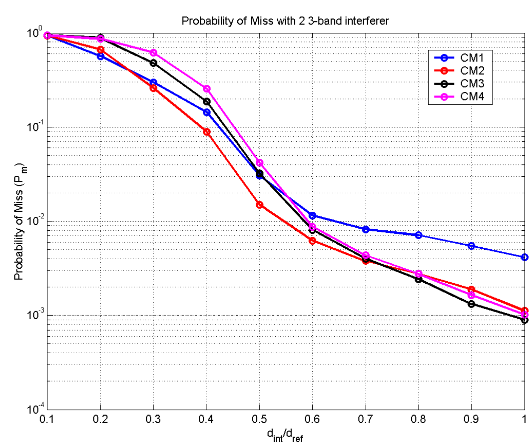
FDMA can be used when enhanced multi-piconet capability is required. The FDMA mode can be defined by specifying the appropriate time-frequency code. For example, if the second sub-band is assigned for a piconet, the time-frequency code is specified as IS = { 2, 2, 2, Repeats}. The maximum number of piconets that can be supported using the FDMA option for Mode 1 and Mode 2 devices are 3 and 7, respectively. Furthermore, when only a single sub-band is assigned for a piconet the transmit power, and hence the sensitivity, will be $10\log_{10}(3)$ dB less for a Mode 1 device. Table 30 tabulates the distance at which N = 2 interferers can be tolerated by a Mode 1 device for a data rate of 110 Mbps, when the reference link is set at a distance of d_{ref} = 6 m. In this test, the reference piconet is assigned band 2, while the interfering piconets are assigned the bands 1 and 3, respectively. The baseband channel select filter is designed to provide an adjacent channel rejection of approximately 15 dB on average.

Table 30 – SOP interference separation distance for Mode 1 (3-band) device with FDMA.

Test Link / Interferer Link	CM1	CM2	CM3
AWGN (N=2) (d_{int}/d_{ref})	2.1 m (0.35)	2.0 m (0.33)	2.0 m (0.33)

The performance of signal acquisition in the presence of a single piconet interferer was also examined. Figure 21 shows the probability of miss detection as a function of the separation distance. To evaluate the simultaneously operating piconet performance, the test link is established such that the reference link is set at a distance of d_{ref} = 0.707 of the 90% link success probability distance. In this simulation, the interferer link was varied across the various channel models. The simulations assume that the reference link uses the first time-frequency code specified in Table 26, while the interfering links uses the remaining time-frequency code specified in Table 26. The results shown in Figure 21 were averaged over a minimum of 50,000 realizations for each multi-path channel environment. The impairments that were included in the system simulations included an offset of ±20 ppm was also assumed at both the transmitter and receiver clock synthesizer, and a 4-bit ADC at the receiver.





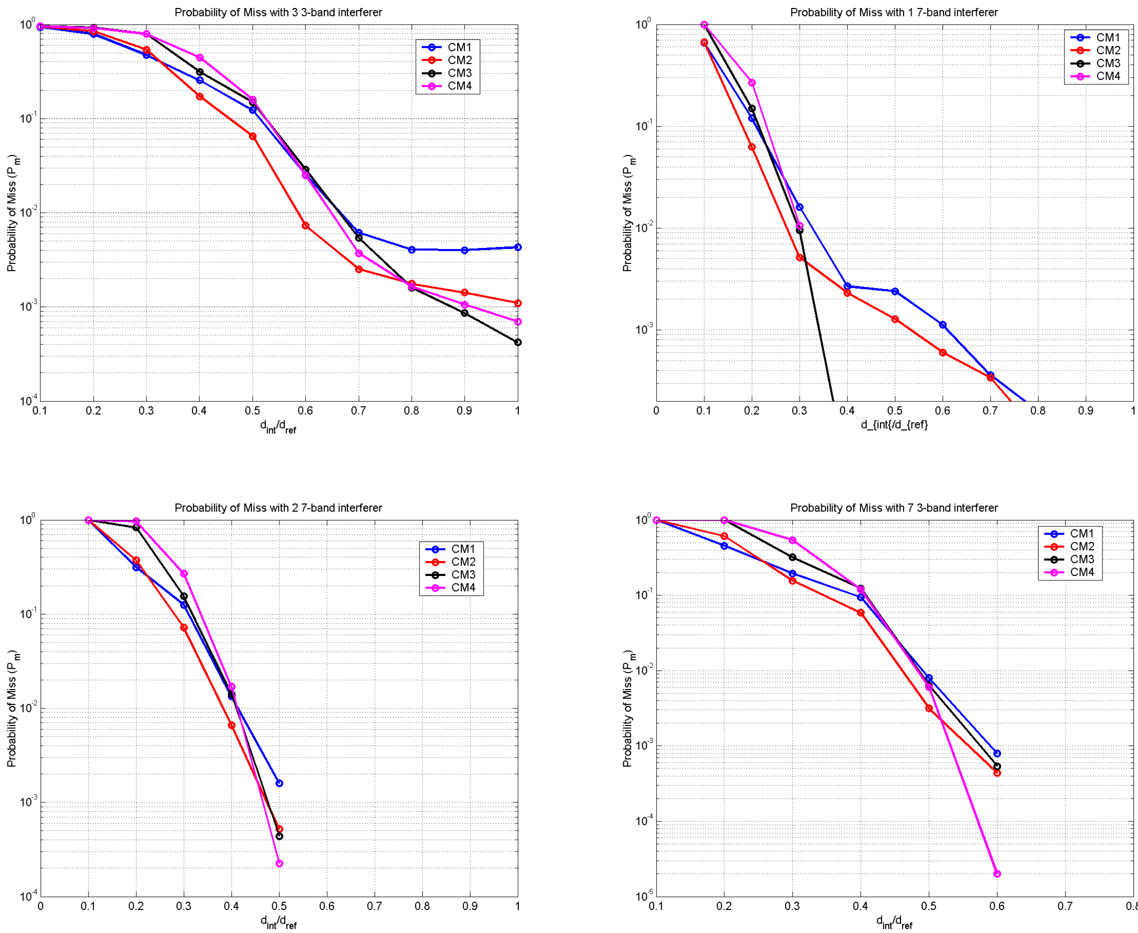


Figure 21 – Probability of miss detection versus separation distance and varying number of 3-band and 7-band interferers.

These figures show that the packet can be acquired at a separation distance of less than 0.4 without significant impact on the packet error rate.

5.4 Signal acquisition

The standard PLCP preamble is designed specifically to be robust in low signal-to-noise environments. In fact, the standard PLCP preamble was designed to operate at 3 dB below sensitivity for an information data rate of 55 Mb/s. Table 31 provides the false alarm and miss detect probabilities for an information data rate of 110 and 200 Mb/s. These probabilities are specified for a single piconet and various channel conditions (AWGN, CM1 through CM4). These results were averaged over 50,000 realizations (500 noise realizations for each of the 100 channel realizations) for a given multi-path channel environment. These results include an offset of ±20 ppm at both the transmitter and receiver clock synthesizer. In addition, a 4-bit ADC was implemented at the receiver.

Table 31 – False detect and miss detect probabilities for a single piconet

Channel Environment	P_m at 110 Mb/s	P_m at 200 Mb/s	P_f	Acquistion Time
AWGN	$< 2 \times 10^{-5}$	$< 2 \times 10^{-5}$	6.2×10^{-4}	< 4.69 µs
CM1	$< 2 \times 10^{-5}$	$< 2 \times 10^{-5}$	6.2×10^{-4}	< 4.69 µs
CM2	$< 2 \times 10^{-5}$	$< 2 \times 10^{-5}$	6.2×10^{-4}	< 4.69 µs
CM3	$< 2 \times 10^{-5}$	$< 2 \times 10^{-5}$	6.2×10^{-4}	< 4.69 µs
CM4	$< 2 \times 10^{-5}$	$< 2 \times 10^{-5}$	6.2×10^{-4}	< 4.69 µs

The probability of miss detection as a function of distance is plotted in Figure 22. This figure shows that the proposed preamble is robust in all multi-path channel environments, even for large distances. Again, these results were averaged over 50,000 realizations (500 noise realizations for each of the 100 channel realizations) for a given multi-path channel environment.

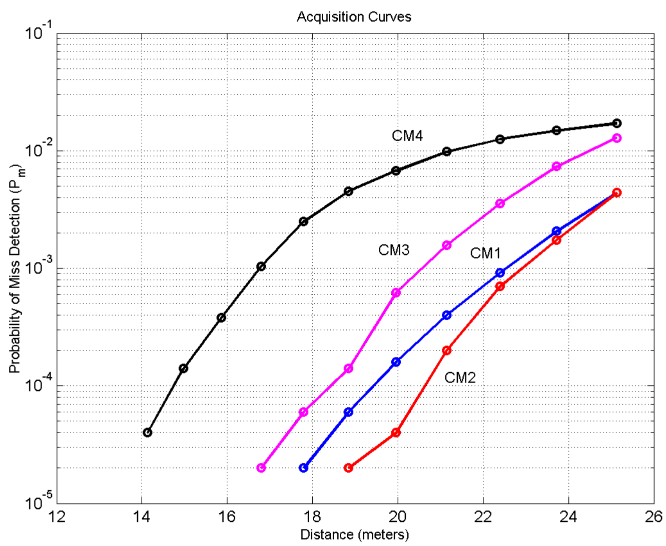


Figure 22 – Probability of miss detection as a function of distance

A timeline showing the overall acquisition process of the standard PLCP preamble is shown in Figure 23. The first 6.5625 µs are used for packet detection and acquisition, coarse frequency estimation, coarse symbol timing estimation, and AGC settling. The next 0.9375 µs are used for synchronization within the preamble, i.e., to determine the location within the preamble, and to indicate the start of the channel estimation sequence. The final 1.875 µs are used for channel estimation, fine frequency estimation, and fine symbol timing estimation.

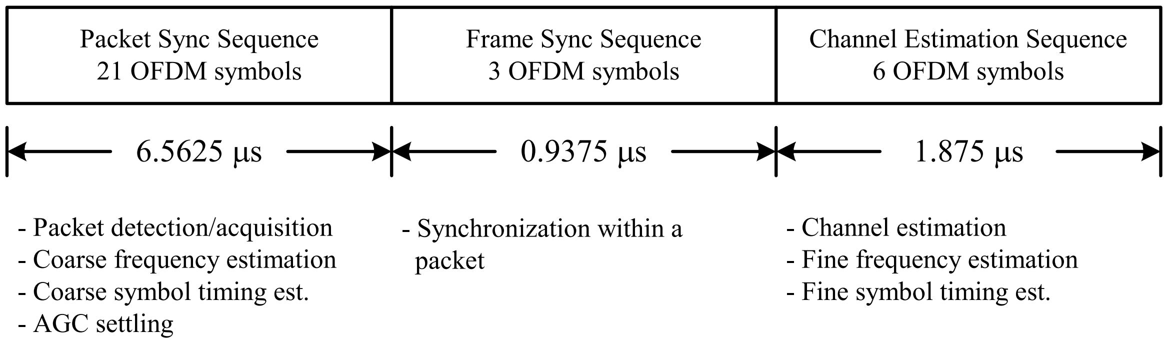


Figure 23 – Timeline for acquisition of the standard PLCP preamble

5.5 System

The performance of the Multi-band OFDM system was evaluated in AWGN and multi-path channel environments specified by the 802.15.3a channel modeling sub-committee report. A path loss decay exponent of 2 was assumed for all the four channel environments and the "new" channel realizations from each of the environments have been used for these simulations. All simulations were performed with at least 500 packets with a payload of 1K bytes each. *The performance simulations incorporate losses due to front-end filtering, clipping at the DAC, ADC degradation (4-bits for 110/200 Mbps and 5-bits for 480 Mbps), multi-path, shadowing, packet acquisition, channel estimation, clock frequency mismatch (± 20 ppm at the TX and RX), carrier offset recovery, carrier tracking, etc.* The PER performance for Mode 1 DEVs in an AWGN channel is shown in Figure 24 as a function of distance and the information data rate.

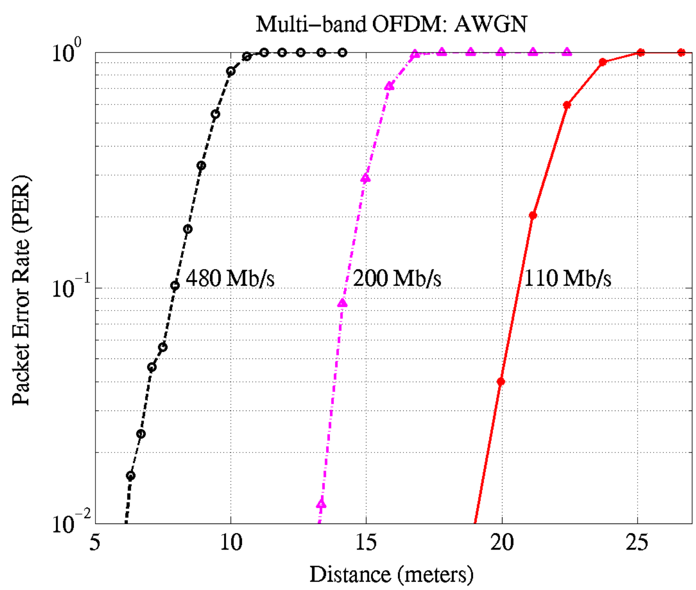


Figure 24 – PER for a Mode 1 DEV as a function of distance and information data rate in an AWGN environment.

The PER performance for the 90th %ile channel realization is illustrated in Figure 25, Figure 26, Figure 27, and Figure 28 as a function of distance for the four channel environments CM1-CM4, respectively. These plots correspond to the performance of the 90th best channel realization, i.e., the worst 10% channels were discarded. This implies that the performance of the Multi-band OFDM system is better than what is illustrated in these plots for at least 90% of the channel realizations from each channel environment.

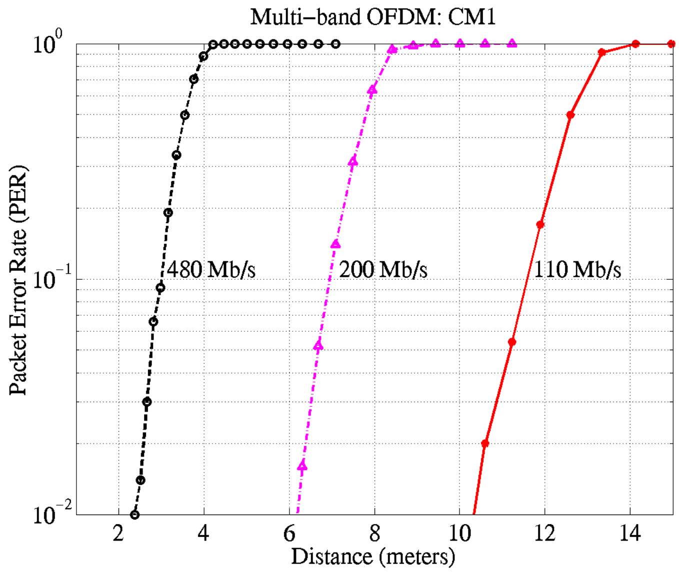


Figure 25 – PER for Mode 1 DEVs as a function of distance and information data rate in a CM1 channel environment for the 90th %ile channel realization.

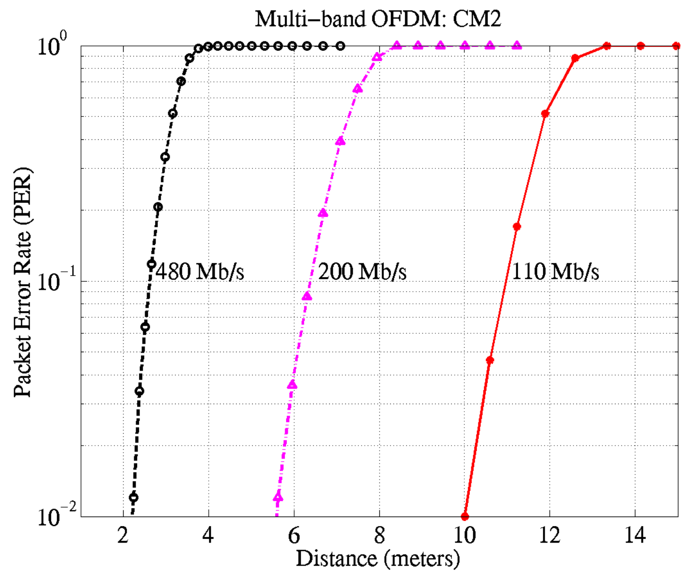


Figure 26 – PER for Mode 1 DEVs as a function of distance and information data rate in a CM2 channel environment for the 90th %ile channel realization.

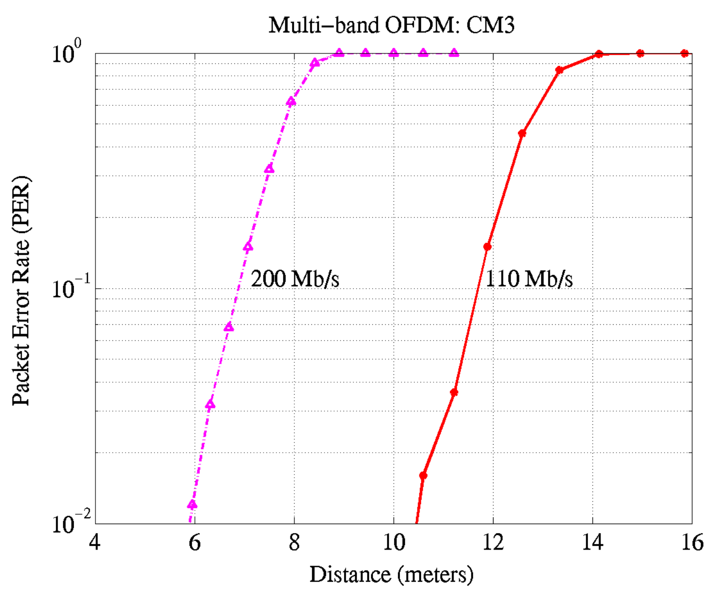


Figure 27 – PER for Mode 1 DEVs as a function of distance and information data rate in a CM3 channel environment for the 90th %ile channel realization.

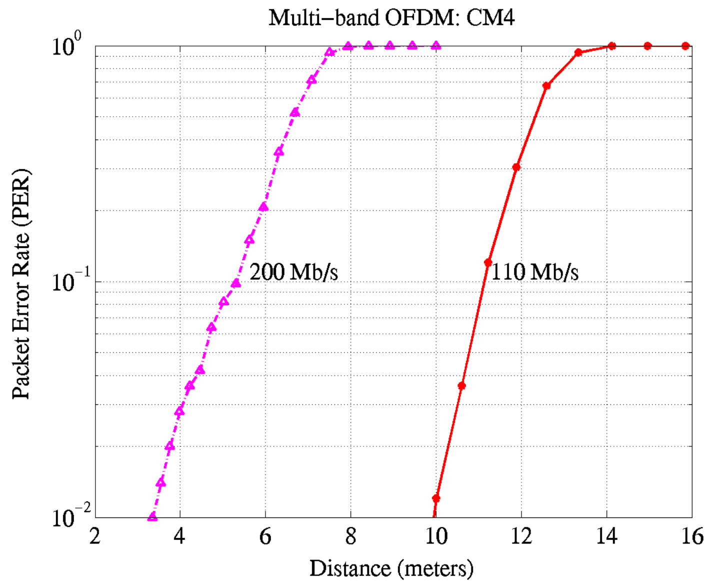


Figure 28 – PER for Mode 1 Devs as a function of distance and information data rate in a CM4 channel environment for the 90th %ile channel realization.

The range at which the Multi-band OFDM system, operating in Mode 1, can achieve a PER of 8% with a link success probability of 90% is listed in **Error! Reference source not found.** for AWGN and the multi-path channel environments. As the link success probability is dominated by shadowing and not by signal acquisition (see Table 31), the link success probability in AWGN channel environment, for the distance values listed in **Error! Reference source not found.**, is close to 100%. In AWGN and all multi-path environments, the Multi-band OFDM system easily satisfies the data rate versus range requirement of 110 Mbps at 10 m and 200 Mbps at 4 m. Furthermore, the Multi-band OFDM system can support data rates of 110 Mbps, 200 Mbps and 480 Mbps at a distance of 10.9-11.6 m, 5-6.9 m and 2.6-2.9 m, respectively, in various multi-path channel environments for a link success probability of 90%.

Table 32 – Range to achieve a PER of 8% with a 90% link success probability for Mode 1 (3-band) devices.

Rate	AWGN	CM1	CM2	CM3	CM4
110 Mb/s	20.5 m	11.4 m	10.7 m	11.5 m	10.9 m
200 Mb/s	14.1 m	6.9 m	6.3 m	6.8 m	4.7 m
480 Mb/s	7.8 m	2.9 m	2.6 m	N/A	N/A

Error! Reference source not found. enumerates the distance at which the mean PER of the 90 best channel realizations is equal to 8%. These values are tabulated for Mode 1 DEVs operating at different data rates and channel environments and are computed by averaging the PER of the 90 best channel realizations for each channel environment.

Table 33 – Range at which the mean PER for the best 90% channels is 8% for Mode 1 (3-band) devices.

Rate	AWGN	CM1	CM2	CM3	CM4
110 Mb/s	20.5 m	14 m	13.2 m	13.8 m	13.8 m
200 Mb/s	14.1 m	8.9 m	8.3 m	8.5 m	7.3 m
480 Mb/s	7.8 m	3.8 m	3.6 m	N/A	N/A

The probability of link success for the four multi-path channel environments is illustrated in **Error! Reference source not found.** for Mode 1 DEVs as a function of distance for an information data rate of 110 Mbps. As the Multi-band OFDM system has been designed to be robust to multi-path and with a sufficiently long cyclic prefix, the performance is similar in the four channel environments. The small variations in performance are primarily due to the effect of shadowing that has been incorporated in the 100 channel realizations corresponding to each of the four channel environments. From **Error! Reference source not found.** we see that the Multi-band OFDM system can support a data rate of 110 Mbps at a distance of about 10.7-11.5 m with a link success probability of 90% and a distance of 13.8-14.7 m for a link success probability of 75 %.

The range at which the Multi-band OFDM system, operating in Mode 2, can achieve a PER of 8% with a link success probability of 90% is listed in Table 34 for AWGN and the multi-path channel environments. The Multi-band OFDM system operating in Mode 2 can support data rates of 110 Mbps, 200 Mbps and 480 Mbps at a distance of 9.0-10.0 m, 4.2-6.4 m and 2.2-2.4 m, respectively, in various multi-path channel environments for a link success probability of 90%.

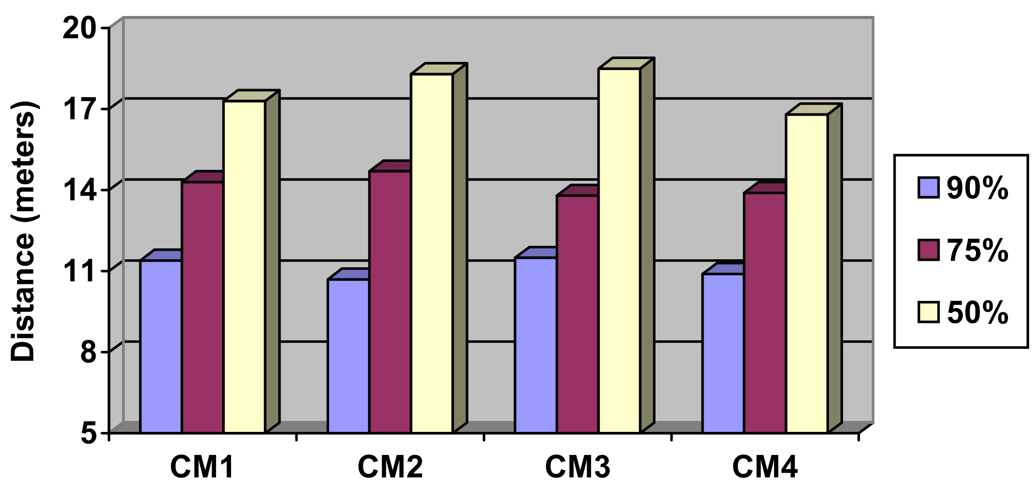


Figure 29 – Range as a function of link success probability and channel environment for an information data rate of 110 Mbps for Mode 1 (3-band) devices.

Table 34 – Range to achieve a PER of 8% with a link success probability of 90% for Mode 2 (7-band) devices.

Rate	AWGN	CM1	CM2	CM3	CM4

110 Mb/s	18.9 m	10.0 m	9.0 m	9.9 m	9.7 m
200 Mb/s	13.0 m	6.4 m	5.7 m	6.4 m	4.2 m
480 Mb/s	7.2 m	2.4 m	2.2 m	N/A	N/A

5.6 Link budget

Parameter: Mode 1 DEV (3-band)	**Value**	**Value**	**Value**
Information data rate (R_b)	110 Mb/s	200 Mb/s	480 Mb/s
Average Tx power (P_T)	−10.3 dBm	−10.3 dBm	−10.3dBm
Tx antenna gain (G_T)	0 dBi	0 dBi	0 dBi
$f_c^{'} = \sqrt{f_{\min} f_{\max}}$: geometric center frequency of waveform ($f_{\min}$ and $f_{\max}$ are the -10 dB edges of the waveform spectrum)	3882 MHz	3882 MHz	3882 MHz
Path loss at 1 meter ($L_1 = 20\log_{10}(4\pi f_c^{'} / c)$) $c = 3\times 10^8$ m/s	44.2 dB	44.2 dB	44.2 dB
Path loss at d m ($L_2 = 20\log_{10}(d)$)	20 dB (d = 10 meters)	12 dB (d = 4 meters)	6 dB (d = 2 meters)
Rx antenna gain (G_R)	0 dBi	0 dBi	0 dBi
Rx power ($P_R = P_T + G_T + G_R - L_1 - L_2$ (dB))	−74.5 dBm	−66.5 dBm	−60.5 dBm
Average noise power per bit ($N = -174 + 10 * \log_{10}(R_b)$)	−93.6 dBm	−91.0 dBm	−87.2 dBm
Rx Noise Figure Referred to the Antenna Terminal (N_F)[1]	6.6 dB	6.6 dB	6.6 dB
Average noise power per bit ($P_N = N + N_F$)	−87.0 dBm	−84.4 dBm	−80.6 dBm
Required E_b/N_0 (S)	4.0 dB	4.7 dB	4.9 dB
Implementation Loss[2] (I)	2.5 dB	2.5 dB	3.0 dB
Link Margin ($M = P_R - P_N - S - I$)	6.0 dB	10.7 dB	12.2 dB
Proposed Min. Rx Sensitivity Level[3]	−80.5 dBm	−77.2 dBm	−72.7 dBm

[1] The primary sources for the noise figure are the LNA and mixer. The voltage gain of the LNA is approximately 15 dB, while the voltage conversion gain of the mixer is approximately 10 dB. The total noise at the output of the LNA is 0.722×10^{-16} V^2/Hz. This value includes the noise of the LNA and the input of resistor. The total noise at the output of the mixer is 0.722×10^{-16} V^2/Hz + $0.1*(8 \times 10^{-9})^2$ V^2/Hz = 0.786×10^{-16} V^2/Hz, where the second term in the addition is generated by the noise sources within the mixer. Thus, the overall noise figure for the analog front-end is $10\log_{10}(7.86/2.56)$ = 4.9 dB. Including the losses associated with the pre-select filter (1.1 dB) and the transmit/receive switch (0.6 dB), the overall noise figure is 6.6 dB.

[2] Includes losses due to cyclic prefix overhead, front-end filtering, clipping at the DAC, ADC degradation, channel estimation, clock frequency mismatch, carrier offset recovery, carrier tracking, etc.

Parameter: Mode 2 DEV (7-band)	**Value**	**Value**	**Value**
Information data rate (R_b)	110 Mb/s	200 Mb/s	480 Mb/s
Average Tx power (P_T)	–6.6 dBm	–6.6 dBm	–6.6dBm
Tx antenna gain (G_T)	0 dBi	0 dBi	0 dBi
$f_c^{'} = \sqrt{f_{\min} f_{\max}}$: geometric center frequency of waveform ($f_{\min}$ and $f_{\max}$ are the -10 dB edges of the waveform spectrum)	5092 MHz	5092 MHz	5092 MHz
Path loss at 1 meter ($L_1 = 20\log_{10}(4\pi f_c^{'} / c)$) $c = 3\times 10^8$ m/s	46.6 dB	46.6 dB	46.6 dB
Path loss at d m ($L_2 = 20\log_{10}(d)$)	20 dB (d = 10 meters)	12 dB (d = 4 meters)	6 dB (d = 2 meters)
Rx antenna gain (G_R)	0 dBi	0 dBi	0 dBi
Rx power ($P_R = P_T + G_T + G_R - L_1 - L_2$ (dB))	–73.2 dBm	–65.2 dBm	–59.2 dBm
Average noise power per bit ($N = -174 + 10 * \log_{10}(R_b)$)	–93.6 dBm	–91.0 dBm	–87.2 dBm
Rx Noise Figure Referred to the Antenna Terminal (N_F)[1]	8.6 dB	8.6 dB	8.6 dB
Average noise power per bit ($P_N = N + N_F$)	–85.0 dBm	–82.4 dBm	–78.6 dBm
Required E_b/N_0 (S)	4.0 dB	4.7 dB	4.9 dB
Implementation Loss[2] (I)	2.5 dB	2.5 dB	3.0 dB
Link Margin ($M = P_R - P_N - S - I$ **)**	5.3 dB	10.0 dB	11.5 dB
Proposed Min. Rx Sensitivity Level[3]	–78.5 dBm	–75.2 dBm	–70.7 dBm

[1] The primary sources for the noise figure are the LNA and mixer. The voltage gain of the LNA is approximately 15 dB, while the voltage conversion gain of the mixer is approximately 10 dB. The total noise at the output of the LNA is 0.909×10^{-16} V^2/Hz. This value includes the noise of the LNA and the input of resistor. The total noise at the output of the mixer is 0.909×10^{-16} V^2/Hz + $0.1*(9 \times 10^{-9})^2$ V^2/Hz = 0.99×10^{-16} V^2/Hz, where the second term in the addition is generated by the noise sources within the mixer. Thus, the overall noise figure for the analog front-end is $10\log_{10}(9.9/2.56)$ = 5.9 dB. Including the losses associated with the pre-select filter (1.8 dB) and the transmit/receive switch (0.9 dB), the overall noise figure is 8.6 dB.

[2] Includes losses due to cyclic prefix overhead, front-end filtering, clipping at the DAC, ADC degradation, channel estimation, clock frequency mismatch, carrier offset recovery, carrier tracking, etc.

5.7 Sensitivity

For a packet error rate (PER) of less than 8% with a PSDU of 1024 bytes, the minimum receiver sensitivity numbers for the various rates and mode of operation are listed in Table 19.

Table 35 – Receiver performance requirements

Data rate (Mb/s)	Minimum sensitivity for Mode 1 DEV (dBm)	Minimum sensitivity for Mode 2 DEV (dBm)
55	–83.5	–81.5
80	–81.7	–79.7
110	–80.5	–78.5
160	–78.7	–76.7
200	–77.2	–75.2
320	–75.1	–73.1
480	–72.7	–70.7

5.8 Power management modes

The proposed PHY system shall support all of the power managements modes (ACTIVE, PSPS, SPS, and HIBERNATE) defined the IEEE 802.15.3 draft standard.

5.9 Power consumption

The power consumption calculations are provided for both a 90 nm CMOS technology node that will be available in early 2004 and a 130 nm CMOS technology node that is currently available. In addition, for the 90/130 nm process node a supply voltage of 1.5/1.8 V was assumed for the analog section of the PHY, except for the LNA where a 2 V supply was assumed. The digital section of the PHY requires a supply voltage of 1.2/1.3 V (for the 90/130 nm process node) and a clock of 132 MHz. Using these assumptions, the power for transmit, receive, clear channel assessment, and power save were calculated. The resulting power consumption values are listed in Table 36 and Table 37.

Table 36 – Power consumption for Mode 1 DEV (3-band)

Process Node	Rate (Mb/s)	Transmit	Receive	CCA	Power Save (Deep Sleep Mode)
90 nm	110	93 mW	155 mW	94 mW	15 μW
	200	93 mW	169 mW	94 mW	15 μW
	480	145 mW	236 mW	94 mW	15 μW
130 nm	110	117 mW	205 mW	117 mW	18 μW
	200	117 mW	227 mW	117 mW	18 μW
	480	180 mW	323 mW	117 mW	18 μW

Table 37 – Power consumption for Mode 2 DEV (7-band)

Process Node	Rate (Mb/s)	Transmit	Receive	CCA	Power Save (Deep Sleep Mode)
90 nm	110	150 mW	209 mW	148 mW	15 μW
	200	150 mW	223 mW	148 mW	15 μW
	480	220 mW	290 mW	148 mW	15 μW
130 nm	110	186 mW	271 mW	183 mW	18 μW
	200	186 mW	293 mW	183 mW	18 μW
	480	253 mW	388 mW	183 mW	18 μW

5.10 Antenna practicality

The antenna is assumed to have the following characteristics across the bandwidth of interest: frequency-independent gain and omni-directional patterns. The remaining requirements for the antenna can be relaxed because OFDM has an inherent robustness against gain, phase, and group delay variation that may be introduced by the antenna. A 16 mm × 13.6 mm x 3 mm antenna with similar characteristics is already commercially available at a low cost and can meet many of the form factors specified in the selection criteria document.