18. Orthogonal frequency division multiplexing (OFDM) PHY specification

18.1 Introduction

18.1.1 General

This clause specifies the PHY entity for an orthogonal frequency division multiplexing (OFDM) system. The OFDM system provides a WLAN with data payload communication capabilities of 6, 9, 12, 18, 24, 36, 48, and 54 Mb/s. The support of transmitting and receiving at data rates of 6, 12, and 24 Mb/s is mandatory. The system uses 52 subcarriers that are modulated using binary or quadrature phase shift keying (BPSK or QPSK) or using 16- or 64-quadrature amplitude modulation (16-QAM or 64-QAM). Forward error correction coding (convolutional coding) is used with a coding rate of 1/2, 2/3, or 3/4.

The OFDM system also provides a “half-clocked” operation using 10 MHz channel spacings with data communications capabilities of 3, 4.5, 6, 9, 12, 18, 24, and 27 Mb/s. The support of transmitting and receiving at data rates of 3, 6, and 12 Mb/s is mandatory when using 10 MHz channel spacing. The half-clocked operation doubles symbol times and clear channel assessment (CCA) times when using 10 MHz channel spacing. The regulatory requirements and information regarding use of this OFDM PHY are in Annex D and Annex E.

The OFDM system also provides a “quarter-clocked” operation using 5 MHz channel spacing with data communication capabilities of 1.5, 2.25, 3, 4.5, 6, 9, 12, and 13.5 Mb/s. The support of transmitting and receiving at data rates of 1.5, 3, and 6 Mb/s is mandatory when using 5 MHz channel spacing. The quarter-clocked operation quadruples symbol times and CCA times when using 5 MHz channel spacing. The regulatory requirements and information regarding use of this OFDM PHY are in Annex D and Annex E.

18.1.2 Scope

Subclause 18.1 describes the PHY services provided to the IEEE 802.11 WLAN MAC by the OFDM PHY. The OFDM PHY consists of two protocol functions, as follows:

a) A PHY convergence function, which adapts the capabilities of the PMD system to the PHY service. This function is supported by the PLCP, which defines a method of mapping the IEEE 802.11 PSDUs into a framing format suitable for sending and receiving user data and management information between two or more STAs using the associated PMD system.

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

18.1.3 OFDM PHY functions

18.1.3.1 General

The OFDM PHY architecture is depicted in the reference model shown in Figure 4-14 (in 4.9). The OFDM PHY contains three functional entities: the PMD function, the PHY convergence function, and the layer management function. Each of these functions is described in detail in 18.1.3.2 to 18.1.3.5.

The OFDM PHY service is provided to the MAC through the PHY service primitives described in Clause 7.

18.1.3.2 PLCP sublayer

In order to allow the IEEE 802.11 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 802.11 MAC services.

18.1.3.3 PMD sublayer

The PMD sublayer provides a means to send and receive data between two or more STAs. This clause is concerned with PHYs using OFDM modulation.

18.1.3.4 PLME

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

18.1.3.5 Service specification method

The models represented by figures and state diagrams are intended to be illustrations of the functions provided. It is important to distinguish between a model and a real implementation. The models are optimized for simplicity and clarity of presentation; the actual method of implementation is left to the discretion of the IEEE 802.11 OFDM-PHY-compliant developer.

The service of a layer or sublayer is the set of capabilities that it offers to a user in the next higher layer (or sublayer). Abstract services are specified here by describing the service primitives and parameters that characterize each service. This definition is independent of any particular implementation.

18.2 OFDM PHY specific service parameter list

18.2.1 Introduction

The architecture of the IEEE 802.11 MAC is intended to be PHY independent. Some PHY implementations require medium management state machines running in the MAC sublayer in order to meet certain PMD requirements. These PHY-dependent MAC state machines reside in a sublayer defined as the 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 service primitives as TXVECTOR and RXVECTOR. The list of these parameters, and the values they may represent, are defined in the specific PHY specifications for each PMD. Subclause 18.2 addresses the TXVECTOR and RXVECTOR for the OFDM PHY.

18.2.2 TXVECTOR parameters

18.2.2.1 General

The parameters in Table 18-1 are defined as part of the TXVECTOR parameter list in the PHY-TXSTART.request primitive.

18.2.2.2 TXVECTOR LENGTH

The allowed values for the LENGTH parameter are in the range of 1 to 4095. This parameter is used to indicate the number of octets in the MPDU which the MAC is currently requesting the PHY to transmit. This value is used by the PHY to determine the number of octet transfers that will occur between the MAC and the PHY after receiving a request to start the transmission.

18.2.2.3 TXVECTOR DATARATE

The DATARATE parameter describes the bit rate at which the PLCP shall transmit the PSDU. Its value takes any of the rates defined in Table 18-1. Data rates of 6, 12, and 24 Mb/s shall be supported for 20 MHz channel spacing, data rates of 3, 6, and 12 Mb/s shall be supported for 10 MHz channel spacing, and data rates of 1.5, 3, and 6 Mb/s shall be supported for 5 MHz channel spacing; other rates may also be supported.

Table 18-1—TXVECTOR parameters

Parameter	Associated primitive	Value
LENGTH	PHY-TXSTART.request (TXVECTOR)	1–4095
DATATRATE	PHY-TXSTART.request (TXVECTOR)	6, 9, 12, 18, 24, 36, 48, and 54 Mb/s for 20 MHz channel spacing (Support of 6, 12, and 24 Mb/s data rates is mandatory.) 3, 4.5, 6, 9, 12, 18, 24, and 27 Mb/s for 10 MHz channel spacing (Support of 3, 6, and 12 Mb/s data rates is mandatory.) 1.5, 2.25, 3, 4.5, 6, 9, 12, and 13.5 Mb/s for 5 MHz channel spacing (Support of 1.5, 3, and 6 Mb/s data rates is mandatory.)
SERVICE	PHY-TXSTART.request (TXVECTOR)	Scrambler initialization; 7 null bits + 9 reserved null bits
TXPWR_LEVEL	PHY-TXSTART.request (TXVECTOR)	1–8
TIME_OF_ DEPARTURE_ REQUESTED	PHY-TXSTART.request (TXVECTOR)	False, true. When true, the MAC entity requests that the PHY PLCP entity measures and reports time of departure parameters corresponding to the time when the first frame energy is sent by the transmitting port; when false, the MAC entity requests that the PHY PLCP entity neither measures nor reports time of departure parameters.

18.2.2.4 TXVECTOR SERVICE

The SERVICE parameter consists of 7 null bits used for the scrambler initialization and 9 null bits reserved for future use.

18.2.2.5 TXVECTOR TXPWR_LEVEL

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

18.2.2.6 TIME_OF_DEPARTURE_REQUESTED

The allowed values are false or true. A parameter value of true indicates that the MAC sublayer is requesting that the PLCP entity provides measurement of when the first frame energy is sent by the transmitting port and reporting within the PHY-TXSTART.confirm(TXSTATUS) primitive. A parameter value of false indicates that the MAC sublayer is requesting that the PLCP entity not provide time of departure measurement nor reporting in the PHY-TXSTART.confirm(TXSTATUS) primitive.

18.2.3 RXVECTOR parameters

18.2.3.1 General

The parameters listed in Table 18-2 are defined as part of the RXVECTOR parameter list in the PHY-RXSTART.indication primitive.

Table 18-2—RXVECTOR parameters

Parameter	Associated primitive	Value
LENGTH	PHY-RXSTART.indication	1–4095
RSSI	PHY-RXSTART.indication (RXVECTOR)	0–RSSI maximum
DATARATE	PHY-RXSTART.request (RXVECTOR)	6, 9, 12, 18, 24, 36, 48, and 54 Mb/s for 20 MHz channel spacing (Support of 6, 12, and 24 Mb/s data rates is mandatory.) 3, 4.5, 6, 9, 12, 18, 24, and 27 Mb/s for 10 MHz channel spacing (Support of 3, 6, and 12 Mb/s data rates is mandatory.) 1.5, 2.25, 3, 4.5, 6, 9, 12, and 13.5 Mb/s for 5 MHz channel spacing (Support of 1.5, 3, and 6 Mb/s data rates is mandatory.)
SERVICE	PHY-RXSTART.request (RXVECTOR)	Null
RCPI (see NOTE)	PHY-RXSTART.indication (RXVECTOR) PHY-RXEND.indication (RXVECTOR)	0–255
ANT_STATE (see NOTE)	PHY-RXSTART.indication (RXVECTOR) PHY-RXEND.indication (RXVECTOR)	0–255
RX_START_OF_FRAME_OFFSET	PHY-RXSTART.indication (RXVECTOR)	0 to 2^{32}– 1. An estimate of the offset (in 10 ns units) from the point in time at which the start of the preamble corresponding to the incoming frame arrived at the receive antenna port to the point in time at which this primitive is issued to the MAC.
NOTE—Parameter is present only when dot11RadioMeasurementActivated is true.		

18.2.3.2 RXVECTOR LENGTH

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

18.2.3.3 RXVECTOR RSSI

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

18.2.3.4 DATARATE

DATARATE shall represent the data rate at which the current PPDU was received. The allowed values of the DATARATE are 6, 9, 12, 18, 24, 36, 48, or 54 Mb/s for 20 MHz channel spacing; 3, 4.5, 6, 9, 12, 18, 24, or 27 Mb/s for 10 MHz channel spacing; and 1.5, 2.25, 3, 4.5, 6, 9, 12, or 13.5 Mb/s for 5 MHz channel spacing.

18.2.3.5 SERVICE

The SERVICE field shall be null.

18.2.3.6 RXVECTOR RCPI

The allowed values for the RCPI parameter are in the range from 0 to 255, as defined in 18.3.10.7. This parameter is a measure by the PHY of the received channel power. RCPI indications of 8 bits are supported. RCPI shall be measured over the entire received frame or by other equivalent means that meet the specified accuracy.

18.2.4 TXSTATUS parameters

18.2.4.1 General

The parameters listed in Table 18-3 are defined as part of the TXSTATUS parameter list in the PHY-TXSTART.confirm service primitive.

Table 18-3—TXSTATUS parameters

Parameter	Associated primitive	Value
TIME_OF_DEPARTURE	PHY-TXSTART.confirm (TXSTATUS)	0 to 2^{32}– 1. The locally measured time when the first frame energy is sent by the transmitting port, in units equal to 1/ TIME_OF_DEPARTURE_ClockRate. This parameter is present only if TIME_OF_DEPARTURE_REQUESTED is true in the corresponding request.
TIME_OF_DEPARTURE_ClockRate	PHY-TXSTART.confirm (TXSTATUS)	0 to 2^{16}– 1. The clock rate, in units of MHz, is used to generate the TIME_OF_DEPARTURE value. This parameter is present only if TIME_OF_DEPARTURE_REQUESTED is true in the corresponding request.
TX_START_OF_FRAME_OFFSET	PHY-TXSTART.confirm (TXSTATUS)	0 to 2^{32}– 1. An estimate of the offset (in 10 ns units) from the point in time at which the start of the preamble corresponding to the frame was transmitted at the transmit antenna port to the point in time at which this primitive is issued to the MAC.

18.2.4.2 TXSTATUS TIME_OF_DEPARTURE

The allowed values for the TIME_OF_DEPARTURE parameter are integers in the range of 0 to 2^{32}– 1. This parameter is used to indicate when the first frame energy is sent by the transmitting port in units equal to 1/ TIME_OF_DEPARTURE_ClockRate. TIME_OF_DEPARTURE may be included in the transmitted frame in order for recipients on multiple channels to determine the time differences of air propagation times between transmitter and recipients and hence to compute the location of the transmitter.

18.2.4.3 TXSTATUS TIME_OF_DEPARTURE_ClockRate

TIME_OF_DEPARTURE_ClockRate indicates the clock rate used for TIME_OF_DEPARTURE.

18.3 OFDM PLCP sublayer

18.3.1 Introduction

Subclause 18.3 provides a convergence procedure in which PSDUs are converted to and from PPDUs. During 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 demodulation and delivery of the PSDU.

18.3.2 PLCP frame format

18.3.2.1 General

Figure 18-1 shows the format for the PPDU including the OFDM PLCP preamble, OFDM PLCP header, PSDU, tail bits, and pad bits. The PLCP header contains the following fields: LENGTH, RATE, a reserved bit, an even parity bit, and the SERVICE field. In terms of modulation, the LENGTH, RATE, reserved bit, and parity bit (with 6 zero tail bits appended) constitute a separate single OFDM symbol, denoted SIGNAL, which is transmitted with the most robust combination of BPSK modulation and a coding rate of R = 1/2. The SERVICE field of the PLCP header and the PSDU (with 6 zero tail bits and pad bits appended), denoted as DATA, are transmitted at the data rate described in the RATE field and may constitute multiple OFDM symbols. The tail bits in the SIGNAL symbol enable decoding of the RATE and LENGTH fields immediately after the reception of the tail bits. The RATE and LENGTH fields are required for decoding the DATA part of the packet. In addition, the CCA mechanism is augmented by predicting the duration of the packet from the contents of the RATE and LENGTH fields, even if the data rate is not supported by the STA. Each of these fields is described in detail in 18.3.3, 18.3.4, and 18.3.5.

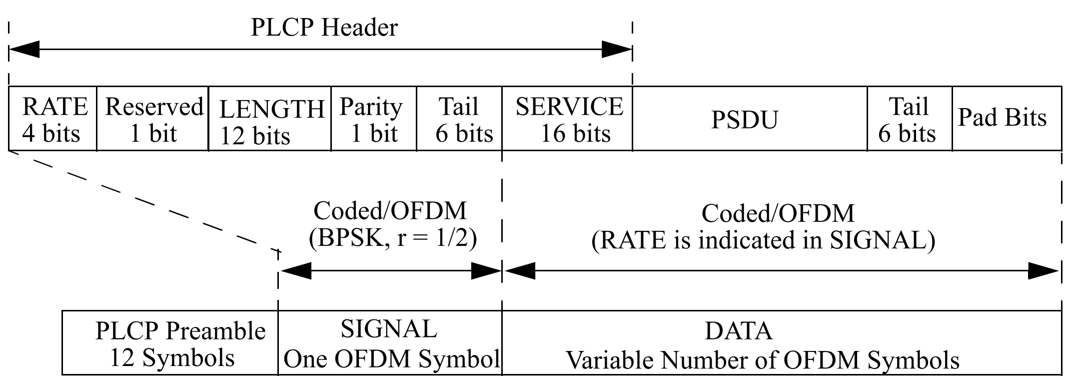

Figure 18-1—PPDU frame format

18.3.2.2 Overview of the PPDU encoding process

The encoding process is composed of many detailed steps, which are described fully in later subclauses, as noted below. The following overview intends to facilitate understanding the details of the convergence procedure:

a) Produce the PLCP Preamble field, composed of 10 repetitions of a "short training sequence" (used for AGC convergence, diversity selection, timing acquisition, and coarse frequency acquisition in the receiver) and two repetitions of a "long training sequence" (used for channel estimation and fine frequency acquisition in the receiver), preceded by a guard interval (GI). Refer to 18.3.3 for details.

b) Produce the PLCP header field from the RATE, LENGTH, and SERVICE fields of the TXVECTOR by filling the appropriate bit fields. The RATE and LENGTH fields of the PLCP header are encoded by a convolutional code at a rate of R = 1/2, and are subsequently mapped onto a single BPSK encoded OFDM symbol, denoted as the SIGNAL symbol. In order to facilitate a reliable and timely detection of the RATE and LENGTH fields, 6 zero tail bits are inserted into the PLCP header. The encoding of the SIGNAL field into an OFDM symbol follows the same steps for convolutional encoding, interleaving, BPSK modulation, pilot insertion, Fourier transform, and prepending a GI as described subsequently for data transmission with BPSK-OFDM modulated at coding rate 1/2. The contents of the SIGNAL field are not scrambled. Refer to 18.3.4 for details.

c) Calculate from RATE field of the TXVECTOR the number of data bits per OFDM symbol (N_{DBPS}), the coding rate (R), the number of bits in each OFDM subcarrier (N_{BPSC}), and the number of coded bits per OFDM symbol (N_{CBPS}). Refer to 18.3.2.3 for details.

d) Append the PSDU to the SERVICE field of the TXVECTOR. Extend the resulting bit string with zero bits (at least 6 bits) so that the resulting length is a multiple of N_{DBPS}. The resulting bit string constitutes the DATA part of the packet. Refer to 18.3.5.4 for details.

e) Initiate the scrambler with a pseudorandom nonzero seed, generate a scrambling sequence, and XOR it with the extended string of data bits. Refer to 18.3.5.5 for details.

f) Replace the six scrambled zero bits following the data with six nonscrambled zero bits. (Those bits return the convolutional encoder to the zero state and are denoted as tail bits.) Refer to 18.3.5.3 for details.

g) Encode the extended, scrambled data string with a convolutional encoder (R = 1/2). Omit (puncture) some of the encoder output string (chosen according to "puncturing pattern") to reach the desired "coding rate." Refer to 18.3.5.6 for details.

h) Divide the encoded bit string into groups of N_{CBPS} bits. Within each group, perform an "interleaving" (reordering) of the bits according to a rule corresponding to the desired RATE. Refer to 18.3.5.7 for details.

i) Divide the resulting coded and interleaved data string into groups of N_{BPSC} bits. For each of the bit groups, convert the bit group into a complex number according to the modulation encoding tables. Refer to 18.3.5.8 for details.

j) Divide the complex number string into groups of 48 complex numbers. Each such group is associated with one OFDM symbol. In each group, the complex numbers are numbered 0 to 47 and mapped hereafter into OFDM subcarriers numbered –26 to –22, –20 to –8, –6 to –1, 1 to 6, 8 to 20, and 22 to 26. The subcarriers –21, –7, 7, and 21 are skipped and, subsequently, used for inserting pilot subcarriers. The 0 subcarrier, associated with center frequency, is omitted and filled with the value 0. Refer to 18.3.5.10 for details.

k) Four subcarriers are inserted as pilots into positions –21, –7, 7, and 21. The total number of the subcarriers is 52 (48 + 4). Refer to 18.3.5.9 for details.

l) For each group of subcarriers –26 to 26, convert the subcarriers to time domain using inverse Fourier transform. Prepend to the Fourier-transformed waveform a circular extension of itself thus forming a GI, and truncate the resulting periodic waveform to a single OFDM symbol length by applying time domain windowing. Refer to 18.3.5.10 for details.

m) Append the OFDM symbols one after another, starting after the SIGNAL symbol describing the RATE and LENGTH fields. Refer to 18.3.5.10 for details.

n) Up-convert the resulting “complex baseband” waveform to an RF according to the center frequency of the desired channel and transmit. Refer to 18.3.2.5 and 18.3.8.2 for details.

An illustration of the transmitted frame and its parts appears in Figure 18-4 (in 18.3.3).

18.3.2.3 Modulation-dependent parameters

The modulation parameters dependent on the data rate used shall be set according to Table 18-4.

Table 18-4—Modulation-dependent parameters

Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})	Data rate (Mb/s) (20 MHz channel spacing)	Data rate (Mb/s) (10 MHz channel spacing)	Data rate (Mb/s) (5 MHz channel spacing)
BPSK	1/2	1	48	24	6	3	1.5
BPSK	3/4	1	48	36	9	4.5	2.25
QPSK	1/2	2	96	48	12	6	3
QPSK	3/4	2	96	72	18	9	4.5
16-QAM	1/2	4	192	96	24	12	6
16-QAM	3/4	4	192	144	36	18	9
64-QAM	2/3	6	288	192	48	24	12
64-QAM	3/4	6	288	216	54	27	13.5

18.3.2.4 Timing related parameters

Table 18-5 is the list of timing parameters associated with the OFDM PLCP.

Table 18-5—Timing-related parameters

Parameter	Value (20 MHz channel spacing)	Value (10 MHz channel spacing)	Value (5 MHz channel spacing)
N_{SD}: Number of data subcarriers	48	48	48
N_{SP}: Number of pilot subcarriers	4	4	4
N_{ST}: Number of subcarriers, total	52 ($N_{SD} + N_{SP}$)	52 ($N_{SD} + N_{SP}$)	52 ($N_{SD} + N_{SP}$)
Δ_F: Subcarrier frequency spacing	0.3125 MHz (=20 MHz/64)	0.15625 MHz (= 10 MHz/64)	0.078125 MHz (= 5 MHz/64)
T_{FFT}: Inverse Fast Fourier Transform (IFFT) / Fast Fourier Transform (FFT) period	3.2 µs ($1/\Delta_F$)	6.4 µs ($1/\Delta_F$)	12.8 µs ($1/\Delta_F$)

Table 18-5—Timing-related parameters *(continued)*

Parameter	Value (20 MHz channel spacing)	Value (10 MHz channel spacing)	Value (5 MHz channel spacing)
$T_{PREAMBLE}$: PLCP preamble duration	16 μs ($T_{SHORT} + T_{LONG}$)	32 μs ($T_{SHORT} + T_{LONG}$)	64 μs ($T_{SHORT} + T_{LONG}$)
T_{SIGNAL}: Duration of the SIGNAL BPSK-OFDM symbol	4.0 μs ($T_{GI} + T_{FFT}$)	8.0 μs ($T_{GI} + T_{FFT}$)	16.0 μs ($T_{GI} + T_{FFT}$)
T_{GI}: GI duration	0.8 μs ($T_{FFT}/4$)	1.6 μs ($T_{FFT}/4$)	3.2 μs ($T_{FFT}/4$)
T_{GI2}: Training symbol GI duration	1.6 μs ($T_{FFT}/2$)	3.2 μs ($T_{FFT}/2$)	6.4 μs ($T_{FFT}/2$)
T_{SYM}: Symbol interval	4 μs ($T_{GI} + T_{FFT}$)	8 μs ($T_{GI} + T_{FFT}$)	16 μs ($T_{GI} + T_{FFT}$)
T_{SHORT}: Short training sequence duration	8 μs ($10 \times T_{FFT}/4$)	16 μs ($10 \times T_{FFT}/4$)	32 μs ($10 \times T_{FFT}/4$)
T_{LONG}: Long training sequence duration	8 μs ($T_{GI2} + 2 \times T_{FFT}$)	16 μs ($T_{GI2} + 2 \times T_{FFT}$)	32 μs ($T_{GI2} + 2 \times T_{FFT}$)

18.3.2.5 Mathematical conventions in the signal descriptions

The transmitted signals are described in a complex baseband signal notation. The actual transmitted signal is related to the complex baseband signal by the following relation:

$$r_{(RF)}\langle t\rangle = Re\{r\langle t\rangle \exp\langle j2\pi f_c t\rangle\} \tag{18-1}$$

where
$Re(.)$ represents the real part of a complex variable
f_c denotes the carrier center frequency

The transmitted baseband signal is composed of contributions from several OFDM symbols.

$$r_{PACKET}(t) = r_{PREAMBLE}(t) + r_{SIGNAL}(t - t_{SIGNAL}) + r_{DATA}(t - t_{DATA}) \tag{18-2}$$

The subframes of which Equation (18-2) are composed are described in 18.3.3, 18.3.4, and 18.3.5.10. The time offsets $t_{SUBFRAME}$ determine the starting time of the corresponding subframe; t_{SIGNAL} is equal to 16 μs for 20 MHz channel spacing, 32 μs for 10 MHz channel spacing, and 64 μs for 5 MHz channel spacing, and t_{DATA} is equal to 20 μs for 20 MHz channel spacing, 40 μs for 10 MHz channel spacing, and 80 μs for 5 MHz channel spacing.

All the subframes of the signal are constructed as an inverse Fourier transform of a set of coefficients, C_k, with C_k defined later as data, pilots, or training symbols in 18.3.3 to 18.3.5.

$$r_{SUBFRAME}(t) = w_{TSUBFRAME}(t) \sum_{k = -N_{ST}/2}^{N_{ST}/2} C_k \exp(j2\pi k\Delta_f)(t - T_{GUARD}) \tag{18-3}$$

The parameters Δ_F and N_{ST} are described in Table 18-5. The resulting waveform is periodic with a period of $T_{FFT} = 1/\Delta_F$. Shifting the time by T_{GUARD} creates the “circular prefix” used in OFDM to avoid ISI from the previous frame. Three kinds of T_{GUARD} are defined: for the short training sequence (= 0 µs), for the long training sequence (= T_{GI2}), and for data OFDM symbols (= T_{GI}). (Refer to Table 18-5.) The boundaries of the subframe are set by a multiplication by a time-windowing function, $w_{TSUBFRAME}(t)$, which is defined as a rectangular pulse, $w_T(t)$, of duration T, accepting the value $T_{SUBFRAME}$. The time-windowing function, $w_T(t)$, depending on the value of the duration parameter, T, may extend over more than one period, T_{FFT}. In particular, window functions that extend over multiple periods of the FFT are utilized in the definition of the preamble. Figure 18-2 illustrates the possibility of extending the windowing function over more than one period, T_{FFT}, and additionally shows smoothed transitions by application of a windowing function, as exemplified in Equation (18-4). In particular, window functions that extend over multiple periods of the FFT are utilized in the definition of the preamble.

$$w_T(t) = \begin{cases} \sin^2\left(\frac{\pi}{2}(0.5 + t/T_{TR})\right) & (-T_{TR}/2 < t < T_{TR}/2) \\ 1 & (T_{TR}/2 \le t < T - T_{TR}/2) \\ \sin^2\left(\frac{\pi}{2}(0.5 - (t-T)/T_{TR})\right) & (T - T_{TR}/2 \le t < T + T_{TR}/2) \end{cases} \tag{18-4}$$

In the case of vanishing T_{TR}, the windowing function degenerates into a rectangular pulse of duration T. The normative specifications of generating the transmitted waveforms shall utilize the rectangular pulse shape. In implementation, higher T_{TR} is typically implemented in order to smooth the transitions between the consecutive subsections. This creates a small overlap between them, of duration T_{TR}, as shown in Figure 18-2. The transition time, T_{TR}, is about 100 ns. Smoothing the transition is required in order to reduce the spectral sidelobes of the transmitted waveform. However, the binding requirements are the spectral mask and modulation accuracy requirements, as detailed in 18.3.9.3 and 18.3.9.7. Time domain windowing, as described here, is just one way to achieve those objectives. The implementer may use other methods to achieve the same goal, such as frequency domain filtering. Therefore, the transition shape and duration of the transition are informative parameters.

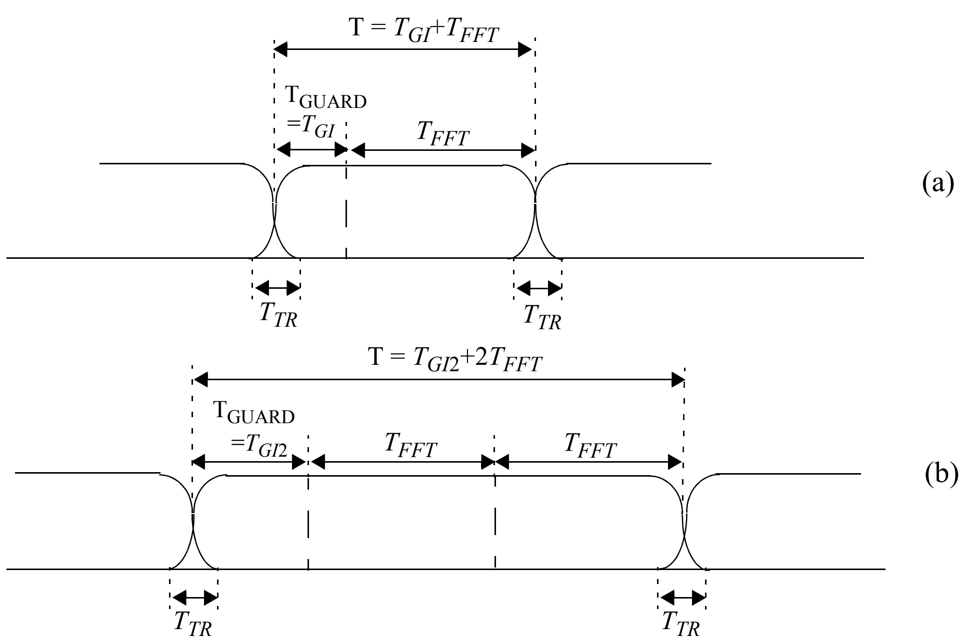

Figure 18-2—Illustration of OFDM frame with cyclic extension and windowing for (a) single reception or (b) two receptions of the FFT period

18.3.2.6 Discrete time implementation considerations

The following descriptions of the discrete time implementation are informational.

In a typical implementation, the windowing function is represented in discrete time. As an example, when a windowing function with parameters T = 4.0 μs and a T_{TR} = 100 ns is applied, and the signal is sampled at 20 Msample/s, it becomes

$$w_T[n] = w_T(nT_S) = \begin{Bmatrix} 1 & 1 \le n \le 79 \\ 0.5 & 0, 80 \\ 0 & otherwise \end{Bmatrix} \tag{18-5}$$

The common way to implement the inverse Fourier transform, as shown in Equation (18-3), is by an IFFT algorithm. If, for example, a 64-point IFFT is used, the coefficients 1 to 26 are mapped to the same numbered IFFT inputs, while the coefficients –26 to –1 are copied into IFFT inputs 38 to 63. The rest of the inputs, 27 to 37 and the 0 (dc) input, are set to 0. This mapping is illustrated in Figure 18-3. After performing an IFFT, the output is cyclically extended to the desired length.

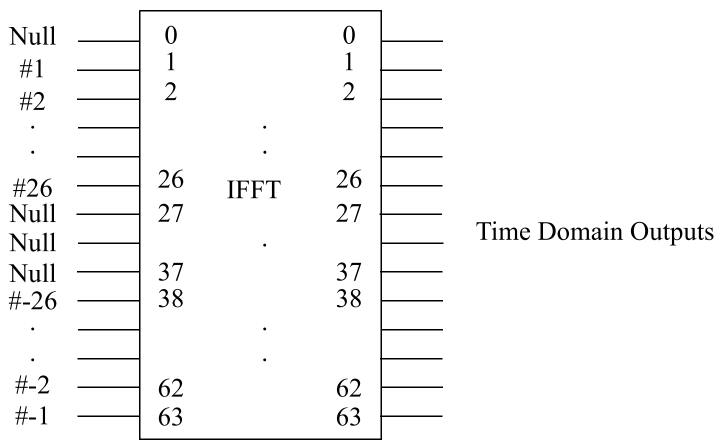

Figure 18-3—Inputs and outputs of inverse Fourier transform

18.3.3 PLCP preamble (SYNC)

The PLCP Preamble field is used for synchronization. It consists of 10 short symbols and two long symbols that are shown in Figure 18-4 and described in this subclause. The timings described in this subclause and shown in Figure 18-4 are for 20 MHz channel spacing. They are doubled for half-clocked (i.e., 10 MHz) channel spacing and are quadrupled for quarter-clocked (i.e., 5 MHz) channel spacing.

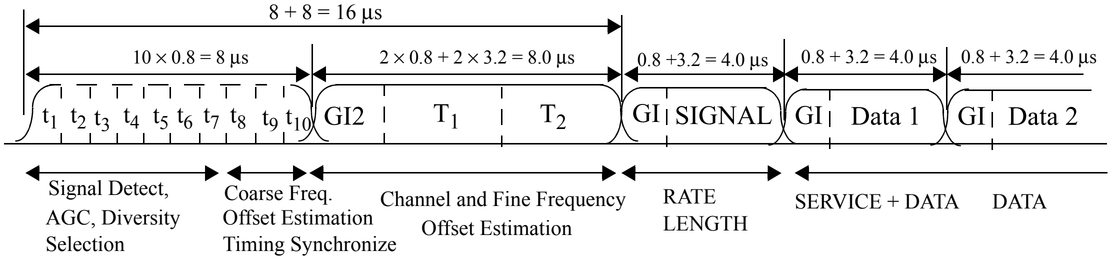

Figure 18-4—OFDM training structure

Figure 18-4 shows the OFDM training structure (PLCP preamble), where t_1 to t_{10} denote short training symbols and T_1 and T_2 denote long training symbols. The PLCP preamble is followed by the SIGNAL field and DATA. The total training length is 16 µs. The dashed boundaries in the figure denote repetitions due to the periodicity of the inverse Fourier transform.

A short OFDM training symbol consists of 12 subcarriers, which are modulated by the elements of the sequence S, given by

$$S_{-26,\,26} = \sqrt{(13/6)} \times \{0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 0,$$

$$0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0,0\} \tag{18-6}$$

The multiplication by a factor of $\sqrt{(13/6)}$ is in order to normalize the average power of the resulting OFDM symbol, which utilizes 12 out of 52 subcarriers.

The signal shall be generated according to the following equation:

$$r_{SHORT}(t) = w_{TSHORT}(t) \sum_{k=-N_{ST}/2}^{N_{ST}/2} S_k \exp(j2\pi k \Delta_F t) \tag{18-7}$$

The fact that only spectral lines of $S_{-26:26}$ with indices that are a multiple of 4 have nonzero amplitude results in a periodicity of $T_{FFT}/4 = 0.8$ µs. The interval T_{SHORT} is equal to ten 0.8 µs periods (i.e., 8 µs).

Generation of the short training sequence is illustrated in Table L-2.

A long OFDM training symbol consists of 53 subcarriers (including the value 0 at dc), which are modulated by the elements of the sequence L, given by

$$L_{-26,\,26} = \{1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 0,$$

$$1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1\} \tag{18-8}$$

A long OFDM training symbol shall be generated according to the following equation:

$$r_{LONG}(t) = w_{TLONG}(t) \sum_{k=-N_{ST}/2}^{N_{ST}/2} L_k \exp(j2\pi k \Delta_F (t - T_{G12})) \tag{18-9}$$

where

$T_{G\,12} = 1.6$ µs

Two periods of the long sequence are transmitted for improved channel estimation accuracy, yielding $T_{LONG} = 1.6 + 2 \times 3.2 = 8$ µs.

An illustration of the long training sequence generation is given in Table L-5.

The sections of short repetitions and long repetitions shall be concatenated to form the preamble

$$r_{PREAMBLE}(t) = r_{SHORT}(t) + r_{LONG}(t - T_{SHORT}) \tag{18-10}$$

18.3.4 SIGNAL field

18.3.4.1 General

The OFDM training symbols shall be followed by the SIGNAL field, which contains the RATE and the LENGTH fields of the TXVECTOR. The RATE field conveys information about the type of modulation and the coding rate as used in the rest of the packet. The encoding of the SIGNAL single OFDM symbol shall be performed with BPSK modulation of the subcarriers and using convolutional coding at R = 1/2. The encoding procedure, which includes convolutional encoding, interleaving, modulation mapping processes, pilot insertion, and OFDM modulation, follows the steps described in 18.3.5.6, 18.3.5.7, and 18.3.5.9, as used for transmission of data with BPSK-OFDM modulated at coding rate 1/2. The contents of the SIGNAL field are not scrambled.

The SIGNAL field shall be composed of 24 bits, as illustrated in Figure 18-5. The four bits 0 to 3 shall encode the RATE. Bit 4 shall be reserved for future use. Bits 5–16 shall encode the LENGTH field of the TXVECTOR, with the LSB being transmitted first.

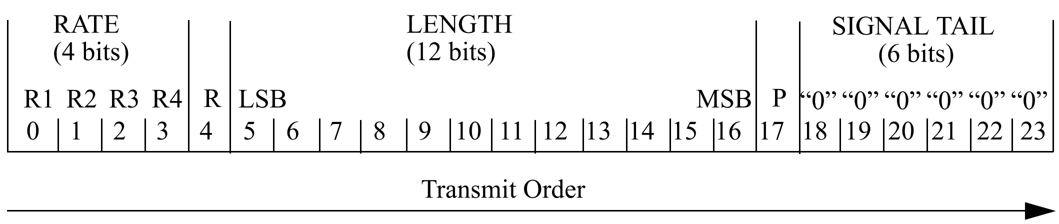

Figure 18-5—SIGNAL field bit assignment

The process of generating the SIGNAL OFDM symbol is illustrated in L.1.4.

18.3.4.2 RATE field

The bits R1–R4 shall be set, dependent on RATE, according to the values in Table 18-6.

Table 18-6—Contents of the SIGNAL field

R1–R4	Rate (Mb/s) (20 MHz channel spacing)	Rate (Mb/s) (10 MHz channel spacing)	Rate (Mb/s) (5 MHz channel spacing)
1101	6	3	1.5
1111	9	4.5	2.25
0101	12	6	3
0111	18	9	4.5
1001	24	12	6
1011	36	18	9
0001	48	24	12
0011	54	27	13.5

18.3.4.3 PLCP LENGTH field

The PLCP LENGTH field shall be an unsigned 12-bit integer that indicates the number of octets in the PSDU that the MAC is currently requesting the PHY to transmit. This value is used by the PHY to determine the number of octet transfers that will occur between the MAC and the PHY after receiving a request to start transmission. The transmitted value shall be determined from the LENGTH parameter in the TXVECTOR issued with the PHY-TXSTART.request primitive described in 7.3.5.5. The LSB shall be transmitted first in time. This field shall be encoded by the convolutional encoder described in 18.3.5.6.

18.3.4.4 Parity (P), Reserved (R), and SIGNAL TAIL fields

Bit 4 is reserved. It shall be set to 0 on transmit and ignored on receive. Bit 17 shall be a positive parity (even parity) bit for bits 0–16. The bits 18–23 constitute the SIGNAL TAIL field, and all 6 bits shall be set to 0.

18.3.5 DATA field

18.3.5.1 General

The DATA field contains the SERVICE field, the PSDU, the TAIL bits, and the PAD bits, if needed, as described in 18.3.5.3 and 18.3.5.4. All bits in the DATA field are scrambled, as described in 18.3.5.5.

18.3.5.2 SERVICE field

The IEEE 802.11 SERVICE field has 16 bits, which shall be denoted as bits 0–15. The bit 0 shall be transmitted first in time. The bits from 0–6 of the SERVICE field, which are transmitted first, are set to 0s and are used to synchronize the descrambler in the receiver. The remaining 9 bits (7–15) of the SERVICE field shall be reserved for future use. All reserved bits shall be set to 0. Refer to Figure 18-6.

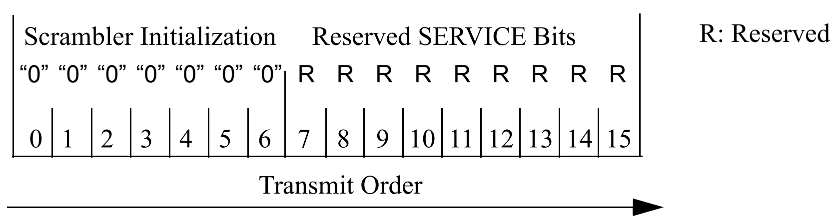

Figure 18-6—SERVICE field bit assignment

18.3.5.3 PPDU TAIL field

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

18.3.5.4 Pad bits (PAD)

The number of bits in the DATA field shall be a multiple of N_{CBPS}, the number of coded bits in an OFDM symbol (48, 96, 192, or 288 bits). To achieve that, the length of the message is extended so that it becomes a multiple of N_{DBPS}, the number of data bits per OFDM symbol. At least 6 bits are appended to the message, in order to accommodate the TAIL bits, as described in 18.3.5.3. The number of OFDM symbols, N_{SYM}; the number of bits in the DATA field, N_{DATA}; and the number of pad bits, N_{PAD}, are computed from the length of the PSDU (LENGTH) as follows:

$$N_{SYM} = \text{Ceiling}\,((16 + 8 \times \text{LENGTH} + 6)/N_{DBPS}) \tag{18-11}$$

$$N_{DATA} = N_{SYM} \times N_{DBPS} \tag{18-12}$$

$$N_{PAD} = N_{DATA} - (16 + 8 \times \text{LENGTH} + 6) \tag{18-13}$$

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 0 and are subsequently scrambled with the rest of the bits in the DATA field.

An example of a DATA field that contains the SERVICE field, DATA, tail, and pad bits is given in L.1.5.1.

18.3.5.5 PLCP DATA scrambler and descrambler

The DATA field, composed of SERVICE, PSDU, tail, and pad parts, shall be scrambled with a length-127 frame-synchronous scrambler. The octets of the PSDU are placed in the transmit serial bit stream, bit 0 first and bit 7 last. The frame synchronous scrambler uses the generator polynomial *S(x)* as follows, and is illustrated in Figure 18-7:

$$S(x) = x^7 + x^4 + 1 \tag{18-14}$$

The 127-bit sequence generated repeatedly by the scrambler shall be (leftmost used first), 00001110 11110010 11001001 00000010 00100110 00101110 10110110 00001100 11010100 11100111 10110100 00101010 11111010 01010001 10111000 1111111, when the all ones initial state is used. The same scrambler is used to scramble transmit data and to descramble receive data. When transmitting, the initial state of the scrambler shall be set to a pseudorandom nonzero state. The seven LSBs of the SERVICE field shall be set to all zeros prior to scrambling to enable estimation of the initial state of the scrambler in the receiver.

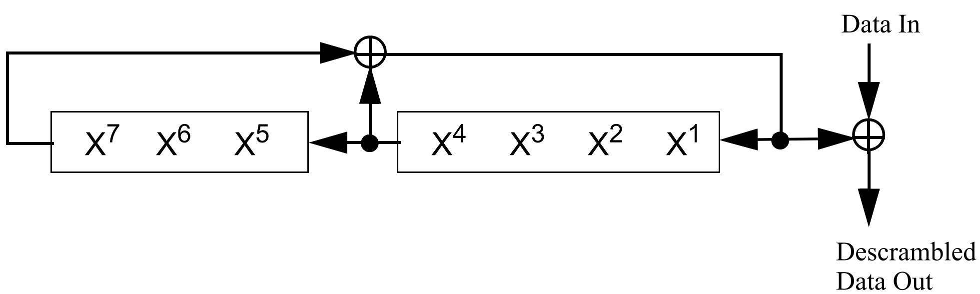

Figure 18-7—Data scrambler

An example of the scrambler output is illustrated in L.1.5.2.

18.3.5.6 Convolutional encoder

The DATA field, composed of SERVICE, PSDU, tail, and pad parts, shall be coded with a convolutional encoder of coding rate R = 1/2, 2/3, or 3/4, corresponding to the desired data rate. The convolutional encoder shall use the industry-standard generator polynomials, $g_0 = 133_8$ and $g_1 = 171_8$, of rate R = 1/2, as shown in Figure 18-8. The bit denoted as "A" shall be output from the encoder before the bit denoted as "B." Higher rates are derived from it 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 18-9. Decoding by the Viterbi algorithm is recommended.

An example of encoding operation is shown in L.1.6.1.

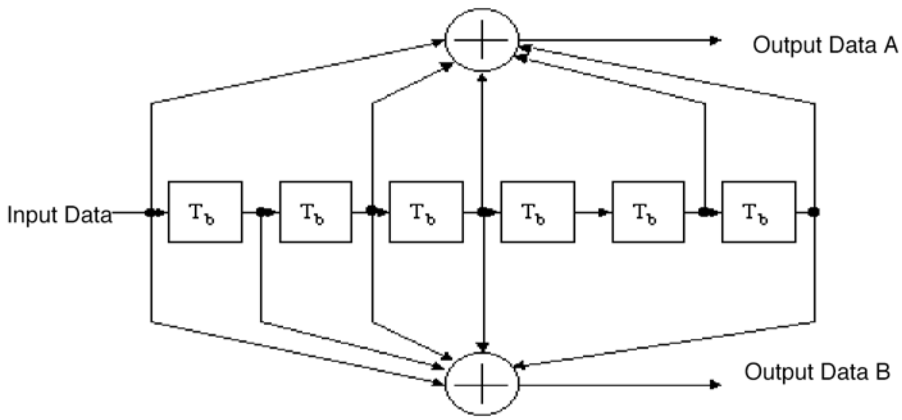

Figure 18-8—Convolutional encoder (k = 7)

18.3.5.7 Data interleaving

All encoded data bits shall be interleaved by a block interleaver with a block size corresponding to the number of bits in a single OFDM symbol, N_{CBPS}. The interleaver is defined by a two-step permutation. The first permutation ensures that adjacent coded bits are mapped onto nonadjacent subcarriers. The second ensures that adjacent coded bits are mapped alternately onto less and more significant bits of the constellation and, thereby, long runs of low reliability (LSB) bits are avoided.

The index of the coded bit before the first permutation shall be denoted by k; i shall be the index after the first and before the second permutation; and j shall be the index after the second permutation, just prior to modulation mapping.

The first permutation is defined by the rule

$$i = (N_{CBPS}/16)\ (k \bmod 16) + \mathrm{Floor}(k/16) \quad k = 0,1,\ldots,N_{CBPS} - 1 \tag{18-15}$$

The function Floor (.) denotes the largest integer not exceeding the parameter.

The second permutation is defined by the rule

$$j = s \times \mathrm{Floor}(i/s) + (i + N_{CBPS} - \mathrm{Floor}(16 \times i/N_{CBPS})) \bmod s \quad i = 0,1,\ldots N_{CBPS} - 1 \tag{18-16}$$

The value of s is determined by the number of coded bits per subcarrier, N_{BPSC}, according to

$$s = \max(N_{BPSC}/2,1) \tag{18-17}$$

The deinterleaver, which performs the inverse relation, is also defined by two permutations.

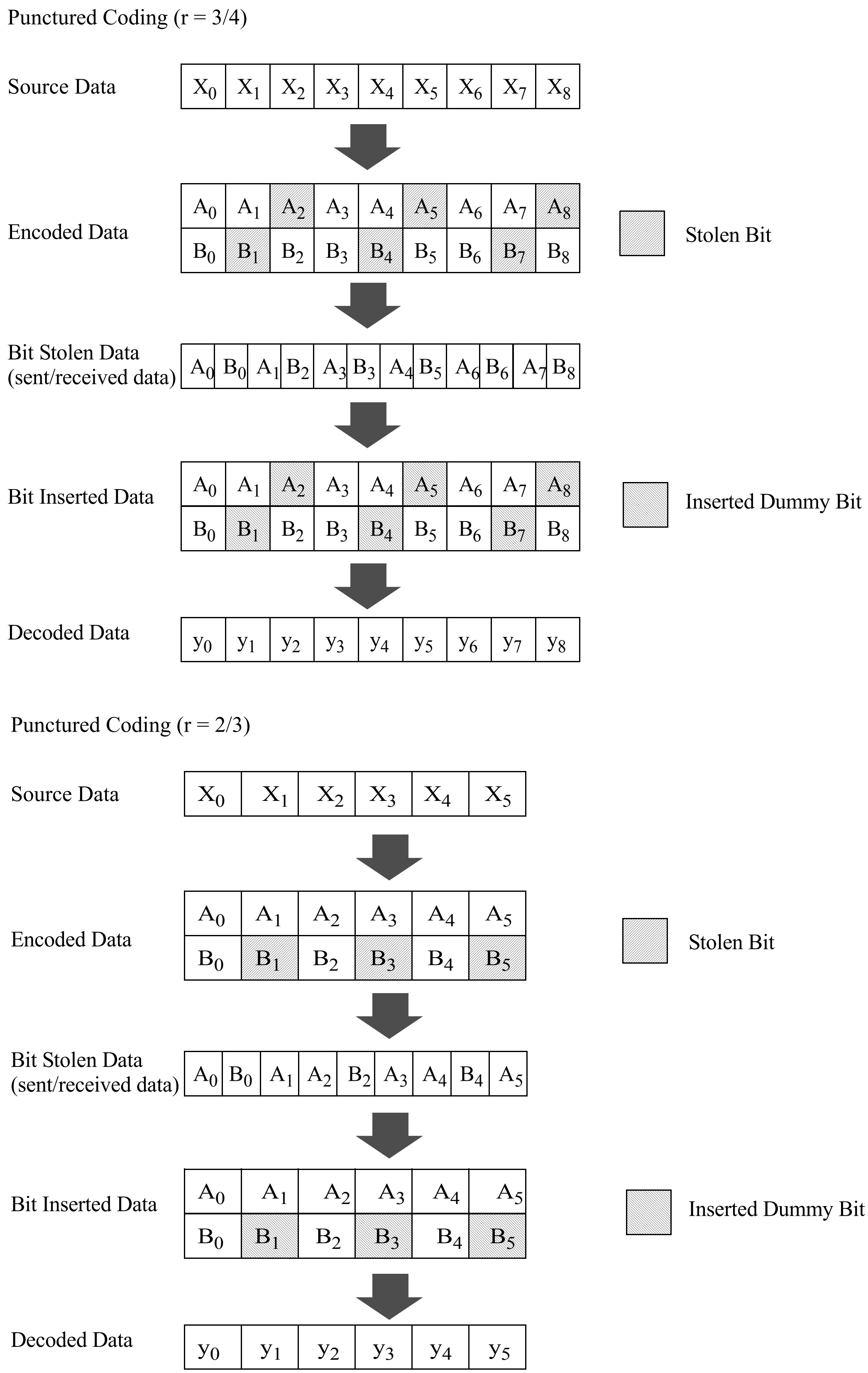

Figure 18-9—Example of the bit-stealing and bit-insertion procedure (r = 3/4, 2/3)

Here the index of the original received bit before the first permutation shall be denoted by j; i shall be the index after the first and before the second permutation; and k shall be the index after the second permutation, just prior to delivering the coded bits to the convolutional (Viterbi) decoder.

The first permutation is defined by the rule

$$i = s \times \mathrm{Floor}(j/s) + (j + \mathrm{Floor}(16 \times j/N_{CBPS})) \bmod s \quad j = 0,1,\ldots N_{CBPS} - 1 \tag{18-18}$$

where

s is defined in Equation (18-17).

This permutation is the inverse of the permutation described in Equation (18-16).

The second permutation is defined by the rule

$$k = 16 \times i - (N_{CBPS} - 1)\mathrm{Floor}(16 \times i/N_{CBPS}) \quad i = 0,1,\ldots N_{CBPS} - 1 \tag{18-19}$$

This permutation is the inverse of the permutation described in Equation (18-15).

An example of interleaving operation is illustrated in L.1.6.2.

18.3.5.8 Subcarrier modulation mapping

The OFDM subcarriers shall be modulated by using BPSK, QPSK, 16-QAM, or 64-QAM, depending on the RATE requested. The encoded and interleaved binary serial input data shall be divided into groups of N_{BPSC} (1, 2, 4, or 6) bits and converted into complex numbers representing BPSK, QPSK, 16-QAM, or 64-QAM constellation points. The conversion shall be performed according to Gray-coded constellation mappings, illustrated in Figure 18-10, 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 K_{MOD}, as described in Equation (18-20).

$$d = (I + jQ) \times K_{MOD} \tag{18-20}$$

The normalization factor, K_{MOD}, depends on the base modulation mode, as prescribed in Table 18-7. Note that the modulation type can be different from the start to the end of the transmission, as the signal changes from SIGNAL to DATA, as shown in Figure 18-1. The purpose of the normalization factor is to achieve the same average power for all mappings. In practical implementations, an approximate value of the normalization factor may be used, as long as the device conforms with the modulation accuracy requirements described in 18.3.9.7.

Table 18-7—Modulation-dependent normalization factor K_{MOD}

Modulation	K_{MOD}
BPSK	1
QPSK	$1/\sqrt{2}$
16-QAM	$1/\sqrt{10}$
64-QAM	$1/\sqrt{42}$

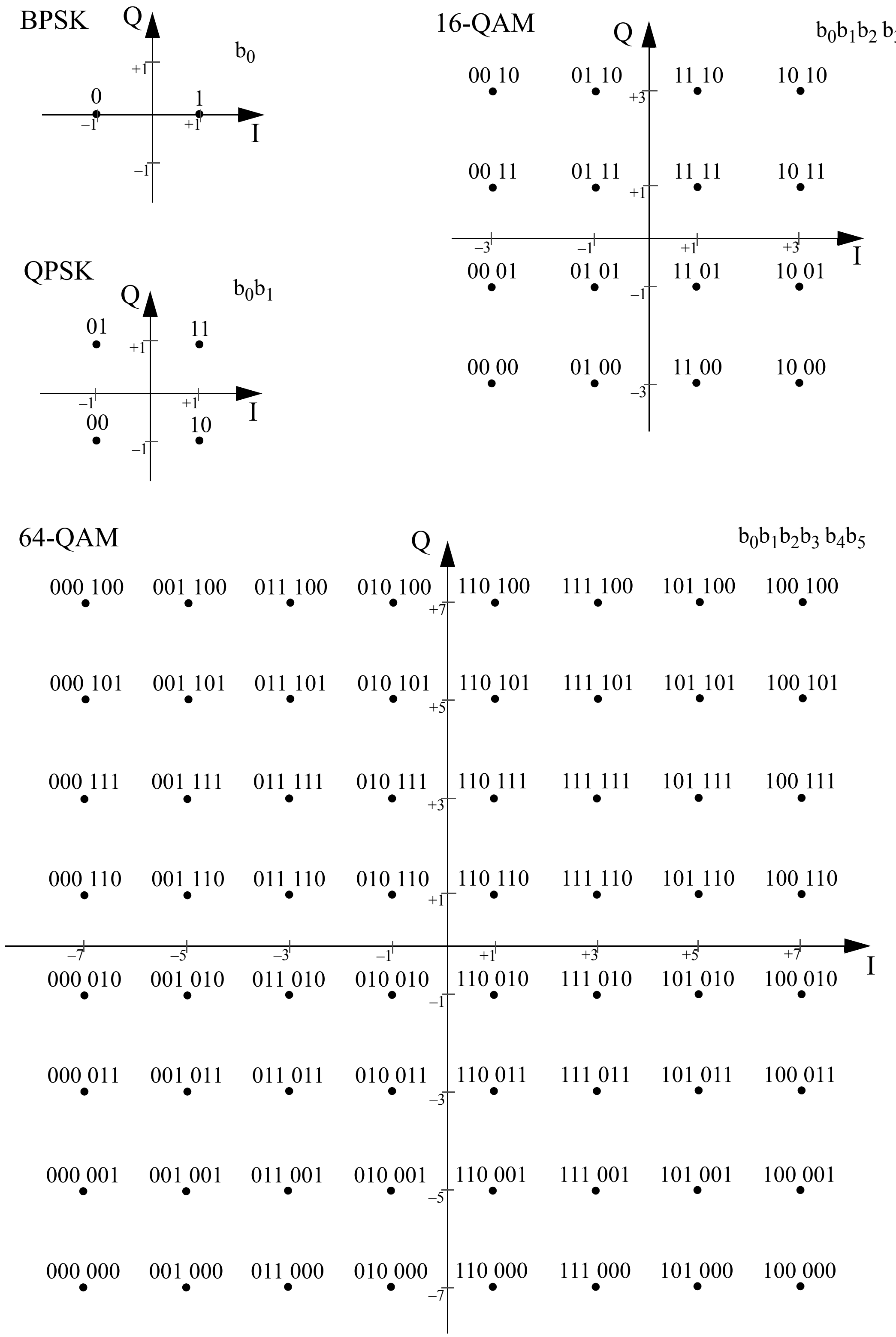

Figure 18-10—BPSK, QPSK, 16-QAM, and 64-QAM constellation bit encoding

For BPSK, b_0 determines the I value, as illustrated in Table 18-8. For QPSK, b_0 determines the I value and b_1 determines the Q value, as illustrated in Table 18-9. For 16-QAM, b_0b_1 determines the I value and b_2b_3 determines the Q value, as illustrated in Table 18-10. For 64-QAM, $b_0b_1b_2$ determines the I value and $b_3b_4b_5$ determines the Q value, as illustrated in Table 18-11.

Table 18-8—BPSK encoding table

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

Table 18-9—QPSK encoding table

Input bit (b_0)	I-out
0	–1
1	1

Input bit (b_1)	Q-out
0	–1
1	1

Table 18-10—16-QAM encoding table

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

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

Table 18-11—64-QAM encoding table

Input bits (b_0 b_1 b_2)	I-out
000	–7
001	–5
011	–3
010	–1
110	1
111	3
101	5
100	7

Input bits (b_3 b_4 b_5)	Q-out
000	–7
001	–5
011	–3
010	–1
110	1
111	3
101	5
100	7

18.3.5.9 Pilot subcarriers

In each OFDM symbol, four of the subcarriers are dedicated to pilot signals in order to make the coherent detection robust against frequency offsets and phase noise. These pilot signals shall be put in subcarriers –21, –7, 7, and 21. The pilots shall be BPSK modulated by a pseudo-binary sequence to prevent the generation of spectral lines. The contribution of the pilot subcarriers to each OFDM symbol is described in 18.3.5.10.

18.3.5.10 OFDM modulation

The stream of complex numbers is divided into groups of $N_{SD} = 48$ complex numbers. This shall be denoted by writing the complex number $d_{k,n}$, which corresponds to subcarrier k of OFDM symbol n, as follows:

$$d_{k,n} \equiv d_{k + N_{SD} \times n}, \qquad k = 0, \ldots N_{SD} - 1,\ n = 0, \ldots N_{SYM} - 1 \tag{18-21}$$

The number of OFDM symbols, N_{SYM}, was introduced in 18.3.5.4.

An OFDM symbol, $r_{DATA,n}(t)$, is defined as

$$\begin{aligned} r_{DATA,n}(t) = w_{TSYM}(t)\Bigg(&\sum_{k=0}^{N_{SD}-1} d_{k,n} \exp\left(\left(j2\pi M(k)\Delta_F(t - T_{GI}\right)\right) \\ &+ p_{n+1} \sum_{k=-N_{ST}/2}^{N_{ST}/2} P_k \exp\left(j2\pi k\Delta_F(t - T_{GI})\right)\Bigg) \end{aligned} \tag{18-22}$$

where the function, $M(k)$, defines a mapping from the logical subcarrier number 0 to 47 into frequency offset index –26 to 26, while skipping the pilot subcarrier locations and the 0^{th} (dc) subcarrier.

$$M(k) = \begin{cases} k - 26 & 0 \le k \le 4 \\ k - 25 & 5 \le k \le 17 \\ k - 24 & 18 \le k \le 23 \\ k - 23 & 24 \le k \le 29 \\ k - 22 & 30 \le k \le 42 \\ k - 21 & 43 \le k \le 47 \end{cases} \tag{18-23}$$

The contribution of the pilot subcarriers for the n^{th} OFDM symbol is produced by inverse Fourier transform of sequence P, given by

$$P_{-26,26} = \{0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0,$$

$$0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, 0, 0, 0, 0, 0\} \tag{18-24}$$

The polarity of the pilot subcarriers is controlled by the sequence, p_n, which is a cyclic extension of the 127 elements sequence and is given by

$$\begin{aligned}p_{0..126v} = \{&1,1,1,1,\ -1,-1,-1,1,\ -1,-1,-1,-1,\ 1,1,-1,1,\ -1,-1,1,1,\ -1,1,1,-1,\ 1,1,1,1,\ 1,1,-1,1,\\ &1,1,-1,1,\ 1,-1,-1,1,\ 1,1,-1,1,\ -1,-1,-1,1,\ -1,1,-1,-1,\ 1,-1,-1,1,\ 1,1,1,1,\ -1,-1,1,1,\\ &-1,-1,1,-1,\ 1,-1,1,1,\ -1,-1,-1,1,\ 1,-1,-1,-1,\ -1,1,-1,-1,\ 1,-1,1,1,\ 1,1,-1,1,\ -1,1,-1,1,\\ &-1,-1,-1,-1,\ -1,1,-1,1,\ 1,-1,1,-1,\ 1,1,1,-1,\ -1,1,-1,-1,\ -1,1,1,1,\ -1,-1,-1,-1,\ -1,-1,-1\}\end{aligned} \tag{18-25}$$

The sequence p_n is generated by the scrambler defined by Figure 18-7 when the all ones initial state is used, and by replacing all 1s with –1 and all 0s with 1. Each sequence element is used for one OFDM symbol. The first element, p_0, multiplies the pilot subcarriers of the SIGNAL symbol, while the elements from p_1 on are used for the DATA symbols.

The subcarrier frequency allocation is shown in Figure 18-11. To avoid difficulties in D/A and A/D converter offsets and carrier feedthrough in the RF system, the subcarrier falling at DC (0^{th} subcarrier) is not used.

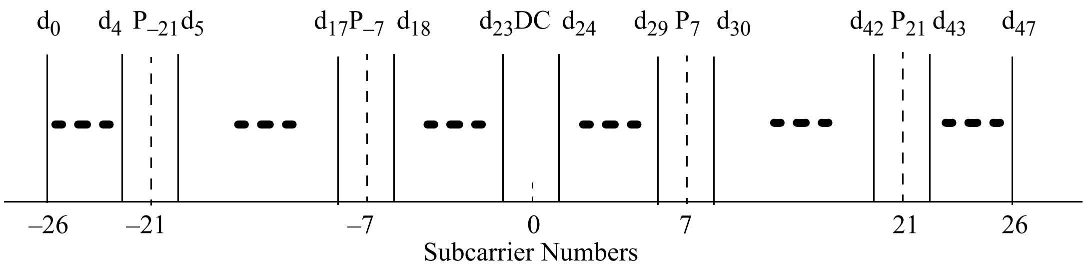

Figure 18-11—Subcarrier frequency allocation

The concatenation of N_{SYM} OFDM symbols is written as

$$r_{DATA}(t) = \sum_{n=0}^{N_{SYM}-1} r_{DATA,n}(t - nT_{SYM}) \tag{18-26}$$

An example of mapping into symbols is shown in L.1.6.3, as well as the scrambling of the pilot signals (see L.1.7). The final output of these operations is also shown in L.1.8.

18.3.6 CCA

PLCP shall provide the capability to perform CCA and report the result to the MAC. The CCA mechanism shall detect a “medium busy” condition with requirements specified in 18.3.10.6 and 18.3.12. This medium status report is indicated by the PHY_CCA.indication primitive.

18.3.7 PLCP data modulation and modulation rate change

The PLCP preamble shall be transmitted using an OFDM modulated fixed waveform. The IEEE 802.11 SIGNAL field, BPSK-OFDM modulated with coding rate 1/2, shall indicate the modulation and coding rate that shall be used to transmit the MPDU. The transmitter (receiver) shall initiate the modulation (demodulation) constellation and the coding rate according to the RATE indicated in the SIGNAL field. The MPDU transmission rate shall be set by the DATARATE parameter in the TXVECTOR, issued with the PHY-TXSTART.request primitive described in 18.2.2.

18.3.8 PMD operating specifications (general)

18.3.8.1 General

General specifications for the BPSK OFDM, QPSK OFDM, 16-QAM OFDM, and 64-QAM OFDM PMD sublayers are provided in 18.3.8.2 to 18.3.8.8. These specifications apply to both the receive and transmit functions and general operation of the OFDM PHY.

18.3.8.2 Outline description

The general block diagram of the transmitter and receiver for the OFDM PHY is shown in Figure 18-12. Major specifications for the OFDM PHY are listed in Table 18-12.

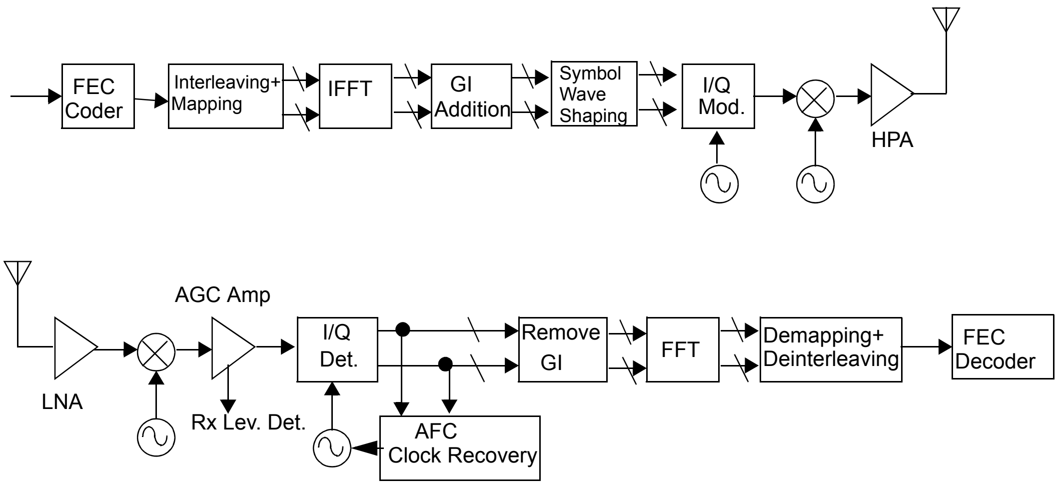

Figure 18-12—Transmitter and receiver block diagram for the OFDM PHY

Table 18-12—Major parameters of the OFDM PHY

Information data rate	**6, 9, 12, 18, 24, 36, 48, and 54 Mb/s (6, 12, and 24 Mb/s are mandatory) (20 MHz channel spacing)**	**3, 4.5, 6, 9, 12, 18, 24, and 27 Mb/s (3, 6, and 12 Mb/s are mandatory) (10 MHz channel spacing)**	**1.5, 2.25, 3, 4.5, 6, 9, 12, and 13.5 Mb/s (1.5, 3, and 6 Mb/s are mandatory) (5 MHz channel spacing)**
Modulation	BPSK OFDM QPSK OFDM 16-QAM OFDM 64-QAM OFDM	BPSK OFDM QPSK OFDM 16-QAM OFDM 64-QAM OFDM	BPSK OFDM QPSK OFDM 16-QAM OFDM 64-QAM OFDM
Error correcting code	K = 7 (64 states) convolutional code	K = 7 (64 states) convolutional code	K = 7 (64 states) convolutional code
Coding rate	1/2, 2/3, 3/4	1/2, 2/3, 3/4	1/2, 2/3, 3/4
Number of subcarriers	52	52	52
OFDM symbol duration	4.0 μs	8.0 μs	16.0 μs
GI	0.8 μs[a] (T_{GI})	1.6 μs (T_{GI})	3.2 μs (T_{GI})
Occupied bandwidth	16.6 MHz	8.3 MHz	4.15 MHz

[a]Refer to 18.3.2.5.

18.3.8.3 Regulatory requirements

WLANs implemented in accordance with this standard are subject to equipment certification and operating requirements established by regional and national regulatory administrations. The PMD specification establishes minimum technical requirements for interoperability, based upon established regulations at the time this standard was issued. These regulations are subject to revision, or may be superseded. Requirements that are subject to local geographic regulations are annotated within the PMD specification. Regulatory requirements that do not affect interoperability are not addressed in this standard. Implementers are referred to the regulatory sources in Annex D for further information. Operation in countries within defined regulatory domains may be subject to additional or alternative national regulations.

18.3.8.4 Operating channel frequencies

18.3.8.4.1 Operating frequency range

The OFDM PHY shall not operate in frequency bands not allocated by a regulatory body in its operational region. Regulatory requirements for a given frequency band are set by the regulatory authority responsible for spectrum management in a given geographic region or domain. The particular channelization to be used for this standard is dependent on such allocation, as well as the associated regulations for use of the allocations. These regulations are subject to revision, or may be superseded.

In some regulatory domains, several frequency bands may be available for OFDM PHY-based WLANs. These bands may be contiguous or not, and different regulatory limits may be applicable. A compliant OFDM PHY shall support at least one frequency band in at least one regulatory domain. The support of specific regulatory domains, and bands within the domains, shall be indicated by PLME attributes dot11RegDomainsImplementedValue and dot11FrequencyBandsImplemented.

The OFDM PHY shall use dot11CurrentFrequency to determine the operating frequency.

18.3.8.4.2 Channel numbering

Channel center frequencies are defined at every integral multiple of 5 MHz above Channel starting frequency. The relationship between center frequency and channel number is given by Equation (18-27):

$$\text{Channel center frequency} = \text{Channel starting frequency} + 5 \times n_{ch} \text{ (MHz)} \tag{18-27}$$

where

$n_{ch} = 1,\ldots 200.$

Channel starting frequency is defined as dot11ChannelStartingFactor × 500 kHz or
is defined as 5 GHz for systems where dot11OperatingClassesRequired is false or not defined.

For example, dot11ChannelStartingFactor = 10000 indicates that Channel 0 center frequency is 5.000 GHz. A channel center frequency of 5.000 GHz shall be indicated by dot11ChannelStartingFactor = 8000 and n_{ch} = 200. An SME managing multiple channel sets can change the channel set being managed by changing the value of dot11ChannelStartingFactor.

This definition provides a unique numbering system for all channels with 5 MHz between center frequencies, as well as the flexibility to define channelization sets for all current and future regulatory domains.

18.3.8.4.3 Channelization

The set of valid operating channel numbers by regulatory domain is defined in Annex E. As shown in Figure 18-11, no subcarrier is allocated on the channel center frequency.

18.3.8.5 Transmit and receive in-band and out-of-band spurious emissions

The OFDM PHY shall conform to in-band and out-of-band spurious emissions as set by regulatory bodies.

18.3.8.6 TX RF delay

The TX RF delay time shall be defined as the time between the issuance of a PMD.DATA.request primitive to the PMD and the start of the corresponding symbol at the air interface.

18.3.8.7 Slot time

The slot time for the OFDM PHY shall be 9 µs for 20 MHz channel spacing, shall be 13 µs for 10 MHz channel spacing, and shall be 21 µs for 5 MHz channel spacing.

Where dot11OperatingClassesRequired is true, the value of the slot time shall be increased by the value of 3 µs × coverage class. The default value of coverage class shall be 0.

NOTE—Distributed coordination function (DCF) operation over larger BSS diameters is facilitated by relaxing some PHY timing parameters, while maintaining compatibility with existing implementations in small BSS diameters.

18.3.8.8 Transmit and receive antenna port impedance

The transmit and receive antenna port(s) impedance shall be 50 Ω if the port is exposed.

18.3.9 PMD transmit specifications

18.3.9.1 General

The transmit specifications associated with the PMD sublayer are described in 18.3.9.2 to 18.3.9.8. In general, these are specified by primitives from the PLCP, and the transmit PMD entity provides the actual means by which the signals required by the PLCP primitives are imposed onto the medium.

18.3.9.2 Transmit power levels

The maximum allowable output power is measured in accordance with practices specified by the appropriate regulatory bodies.

18.3.9.3 Transmit spectrum mask

The transmit spectrum mask by regulatory domain is defined in Annex D and Annex E.

NOTE—In the presence of additional regulatory restrictions, the device needs to meet both the regulatory requirements and the mask defined here, i.e., its emissions need to be no higher at any frequency offset than the minimum of the values specified in the regulatory and default masks.

For operation using 20 MHz channel spacing, the transmitted spectrum shall have a 0 dBr (dB relative to the maximum spectral density of the signal) bandwidth not exceeding 18 MHz, –20 dBr at 11 MHz frequency offset, –28 dBr at 20 MHz frequency offset, and the maximum of –40 dBr and –53 dBm/MHz at 30 MHz frequency offset and above. The transmitted spectral density of the transmitted signal shall fall within the spectral mask, as shown in Figure 18-13. The measurements shall be made using a 100 kHz resolution bandwidth and a 30 kHz video bandwidth.

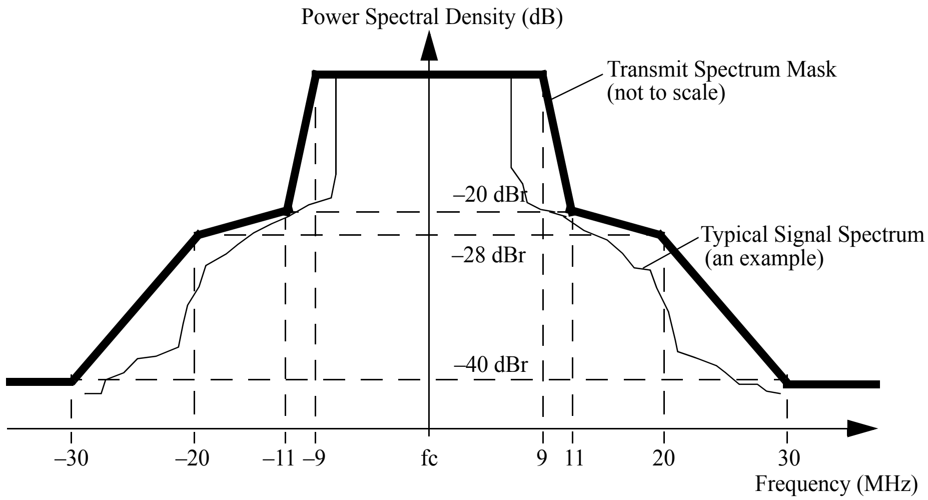

Figure 18-13—Transmit spectrum mask for 20 MHz transmission

For operation using 10 MHz channel spacing, the transmitted spectrum shall have a 0 dBr bandwidth not exceeding 9 MHz, –20 dBr at 5.5 MHz frequency offset, –28 dBr at 10 MHz frequency offset, and the maximum of –40 dBr and –50 dBm/MHz at 15 MHz frequency offset and above. The transmitted spectral density of the transmitted signal shall fall within the spectral mask, as shown in Figure 18-14. The measurements shall be made using a 100 kHz resolution bandwidth and a 30 kHz video bandwidth.

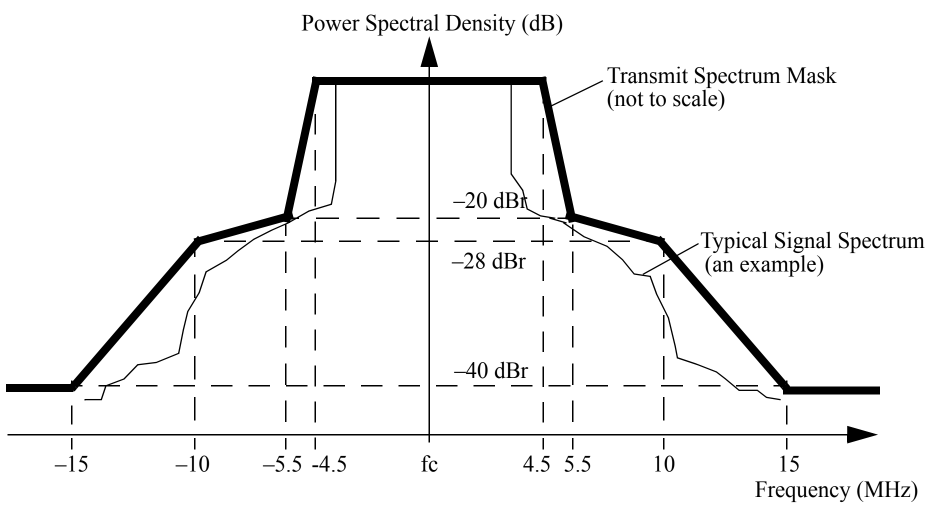

Figure 18-14—Transmit spectrum mask for 10 MHz transmission

For operation using 5 MHz channel spacing, the transmitted spectrum shall have a 0 dBr bandwidth not exceeding 4.5 MHz, –20 dBr at 2.75 MHz frequency offset, –28 dBr at 5 MHz frequency offset, and the maximum of –40 dBr and –47 dBm/MHz at 7.5 MHz frequency offset and above. The transmitted spectral density of the transmitted signal shall fall within the spectral mask, as shown in Figure 18-15. The measurements shall be made using a 100 kHz resolution bandwidth and a 30 kHz video bandwidth.

18.3.9.4 Transmission spurious

Spurious transmissions from compliant devices shall conform to national regulations.

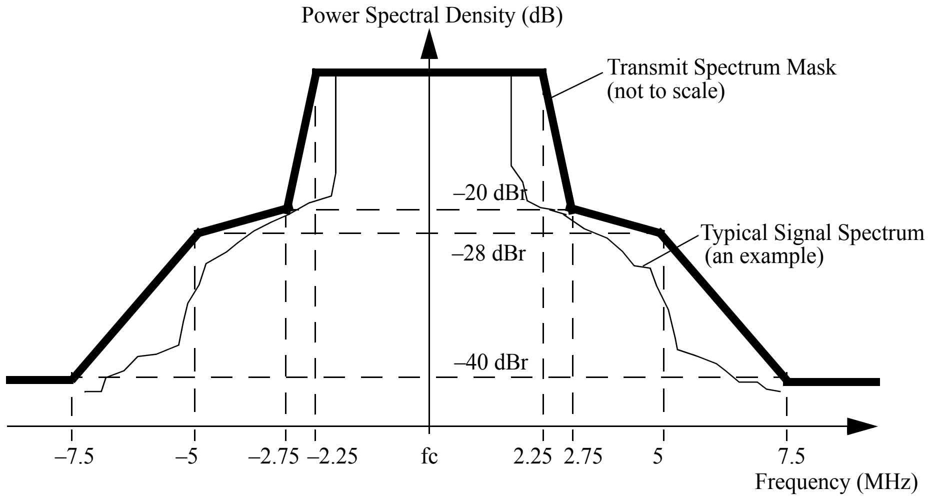

Figure 18-15—Transmit spectrum mask for 5 MHz transmission

18.3.9.5 Transmit center frequency tolerance

The transmitted center frequency tolerance shall be ±20 ppm maximum for 20 MHz and 10 MHz channels and shall be ±10 ppm maximum for 5 MHz channels. The transmit center frequency and the symbol clock frequency shall be derived from the same reference oscillator.

18.3.9.6 Symbol clock frequency tolerance

The symbol clock frequency tolerance shall be ±20 ppm maximum for 20 MHz and 10 MHz channels, and shall be ±10 ppm maximum for 5 MHz channels. The transmit center frequency and the symbol clock frequency shall be derived from the same reference oscillator.

18.3.9.7 Modulation accuracy

18.3.9.7.1 Introduction

Transmit modulation accuracy specifications are described in 18.3.9.7. The test method is described in 18.3.9.8.

18.3.9.7.2 Transmitter center frequency leakage

Certain transmitter implementations may cause leakage of the center frequency component. Such leakage (which manifests itself in a receiver as energy in the center frequency component) shall not exceed –15 dB relative to overall transmitted power or, equivalently, +2 dB relative to the average energy of the rest of the subcarriers. The data for this test shall be derived from the channel estimation phase.

18.3.9.7.3 Transmitter spectral flatness

The average energy of the constellations in each of the spectral lines –16.. –1 and +1.. +16 shall deviate no more than ± 4 dB from their average energy. The average energy of the constellations in each of the spectral lines –26.. –17 and +17.. +26 shall deviate no more than +4/–6 dB from the average energy of spectral lines –16.. –1 and +1.. +16. The data for this test shall be derived from the channel estimation step.

18.3.9.7.4 Transmitter constellation error

The relative constellation RMS error, averaged over subcarriers, OFDM frames, and packets, shall not exceed a data-rate dependent value according to Table 18-13.

Table 18-13—Allowed relative constellation error versus data rate

Relative constellation error (dB)	Modulation	Coding rate (R)
–5	BPSK	1/2
–8	BPSK	3/4
–10	QPSK	1/2
–13	QPSK	3/4
–16	16-QAM	1/2
–19	16-QAM	3/4
–22	64-QAM	2/3
–25	64-QAM	3/4

18.3.9.8 Transmit modulation accuracy test

The transmit modulation accuracy test shall be performed by instrumentation capable of converting the transmitted signal into a stream of complex samples at 20 Msample/s or more, with sufficient accuracy in terms of I/Q arm amplitude and phase balance, dc offsets, phase noise, etc. A possible embodiment of such a setup is converting the signal to a low IF with a microwave synthesizer, sampling the signal with a digital oscilloscope and decomposing it digitally into quadrature components.

The sampled signal shall be processed in a manner similar to an actual receiver, according to the following steps, or an equivalent procedure:

a) Start of frame shall be detected.

b) Transition from short sequences to channel estimation sequences shall be detected, and fine timing (with one sample resolution) shall be established.

c) Coarse and fine frequency offsets shall be estimated.

d) The packet shall be derotated according to estimated frequency offset.

e) The complex channel response coefficients shall be estimated for each of the subcarriers.

f) For each of the data OFDM symbols: transform the symbol into subcarrier received values, estimate the phase from the pilot subcarriers, derotate the subcarrier values according to estimated phase, and divide each subcarrier value with a complex estimated channel response coefficient.

g) For each data-carrying subcarrier, find the closest constellation point and compute the Euclidean distance from it.

h) Compute the RMS average of all errors in a packet. It is given by

$$Error_{RMS} = \frac{\sum_{i=1}^{N_f} \sqrt{\frac{\sum_{j=1}^{L_P}\left[\sum_{k=1}^{52}\{(I(i,j,k)-I_0(i,j,k))^2+(Q(i,j,k)-Q_0(i,j,k))^2\}\right]}{52L_P \times P_0}}}{N_f} \tag{18-28}$$

where

L_P is the length of the packet;

N_f is the number of frames for the measurement;

$(I_0(i,j,k), Q_0(i,j,k))$denotes the ideal symbol point of the i^{th} frame, j^{th} OFDM symbol of the frame, k^{th} subcarrier of the OFDM symbol in the complex plane;

$(I(i,j,k), Q(i,j,k))$denotes the observed point of the i^{th} frame, j^{th} OFDM symbol of the frame, k^{th} subcarrier of the OFDM symbol in the complex plane (see Figure 18-16);

P_0 is the average power of the constellation.

The vector error on a phase plane is shown in Figure 18-16.

The test shall be performed over at least 20 frames (N_f), and the RMS average shall be taken. The packets under test shall be at least 16 OFDM symbols long. Random data shall be used for the symbols.

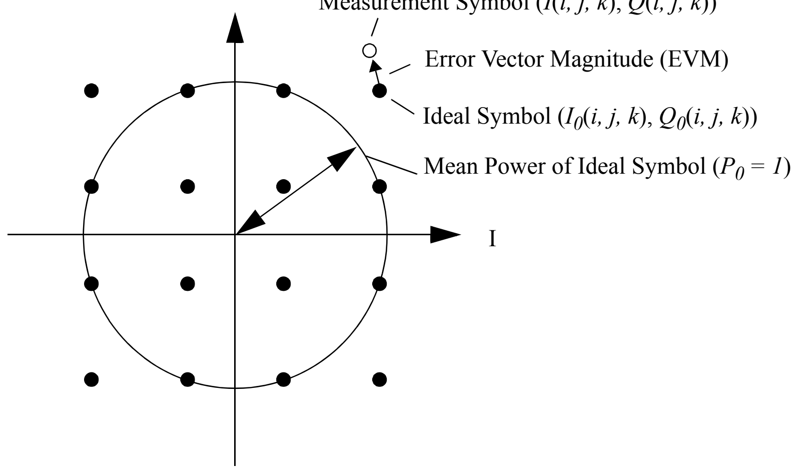

Figure 18-16—Constellation error

18.3.9.9 Time of Departure accuracy

The Time of Departure accuracy test evaluates TIME_OF_DEPARTURE against aTxPmdTxStartRMS and aTxPmdTxStartRMS against TIME_OF_DEPARTURE_ACCURACY_TEST_THRESH as defined Annex T with the following test parameters:

— MULTICHANNEL_SAMPLING_RATE is $20 \times 10^6\left(1 + \left\lceil \frac{f_H - f_L}{20\text{ MHz}} \right\rceil\right)$ sample/s

where

f_H is the nominal center frequency in Hz of the highest channel in the channel set

f_L is the nominal center frequency in Hz of the lowest channel in the channel set, the channel set is the set of channels upon which frames providing measurements are transmitted, the channel set comprises channels uniformly spaced across $f_H - f_L \geq 50$ MHz

$\lceil x \rceil$ equals the smallest integer equal to or larger than x

— FIRST_TRANSITION_FIELD is the Short symbols.
— SECOND_TRANSITION_FIELD is the Long symbols.
— TRAINING_FIELD is the Long symbols windowed in a manner which should approximate the windowing described in 18.3.2.5 with T_{TR} = 100 ns for 20 MHz channel spacing, T_{TR} = 200 ns for 10 MHz channel spacing and T_{TR} = 400 ns for 5 MHz channel spacing.
— TIME_OF_DEPARTURE_ACCURACY_TEST_THRESH is 80 ns.

NOTE—The indicated windowing applies to the time of departure accuracy test equipment, and not the transmitter or receiver.

18.3.10 PMD receiver specifications

18.3.10.1 Introduction

The receive specifications associated with the PMD sublayer are described in 18.3.10.2 to 18.3.10.6.

18.3.10.2 Receiver minimum input sensitivity

The packet error ratio (PER) shall be 10% or less when the PSDU length is 1000 octets and the rate-dependent input level is as shown in Table 18-14. The minimum input levels are measured at the antenna connector (noise factor of 10 dB and 5 dB implementation margins are assumed).

Table 18-14—Receiver performance requirements

Modulation	Coding rate (R)	Adjacent channel rejection (dB)	Alternate adjacent channel rejection (dB)	Minimum sensitivity (dBm) (20 MHz channel spacing)	Minimum sensitivity (dBm) (10 MHz channel spacing)	Minimum sensitivity (dBm) (5 MHz channel spacing)
BPSK	1/2	16	32	–82	–85	–88
BPSK	3/4	15	31	–81	–84	–87
QPSK	1/2	13	29	–79	–82	–85
QPSK	3/4	11	27	–77	–80	–83
16-QAM	1/2	8	24	–74	–77	–80
16-QAM	3/4	4	20	–70	–73	–76
64-QAM	2/3	0	16	–66	–69	–72
64-QAM	3/4	–1	15	–65	–68	–71

18.3.10.3 Adjacent channel rejection

The adjacent channel rejection shall be measured by setting the desired signal's strength 3 dB above the rate-dependent sensitivity specified in Table 18-14 and raising the power of the interfering signal until 10% PER is caused for a PSDU length of 1000 octets. The power difference between the interfering and the desired channel is the corresponding adjacent channel rejection. The interfering signal in the adjacent channel shall be a conformant OFDM signal, unsynchronized with the signal in the channel under test. For a conformant OFDM PHY the corresponding rejection shall be no less than specified in Table 18-14.

An optional enhanced performance specification is provided for systems requiring improved immunity to out-of-channel interfering emissions. If a STA has dot11ACRType equal to 2, the adjacent channel rejection shall be no less than specified in Table 18-15. The interfering signal in the adjacent channel shall be a conformant OFDM signal, using transmit mask M (see D.2.4), unsynchronized with the signal in the channel under test. The corresponding minimum receiver sensitivities for each modulation and coding rate are the same as in Table 18-14.

NOTE—Transmit mask M is equivalent to class C (see D.2.2).

Table 18-15—Optional enhanced receiver performance requirements

Modulation	Coding rate (R)	Adjacent channel rejection (dB)	Nonadjacent channel rejection (dB)
BPSK	1/2	28	42
BPSK	3/4	27	41
QPSK	1/2	25	39
QPSK	3/4	23	37
16-QAM	1/2	20	34
16-QAM	3/4	16	30
64-QAM	2/3	12	26
64-QAM	3/4	11	25

18.3.10.4 Nonadjacent channel rejection

The nonadjacent channel rejection shall be measured by setting the desired signal's strength 3 dB above the rate-dependent sensitivity specified in Table 18-14, and raising the power of the interfering signal until a 10% PER occurs for a PSDU length of 1000 octets. The power difference between the interfering and the desired channel is the corresponding nonadjacent channel rejection. The interfering signal in the nonadjacent channel shall be a conformant OFDM signal, unsynchronized with the signal in the channel under test. For a conformed OFDM PHY, the corresponding rejection shall be no less than specified in Table 18-14.

An optional enhanced performance specification is provided for systems requiring improved immunity to out-of-channel interfering emissions. If a STA has dot11ACRType equal to 2, the nonadjacent channel rejection shall be no less than specified in Table 18-15. The interfering signal in the nonadjacent channel shall be a conformant OFDM signal, using transmit mask M (see D.2.4), unsynchronized with the signal in the channel under test. The corresponding minimum receiver sensitivities for each modulation and coding rate are the same as in Table 18-14.

18.3.10.5 Receiver maximum input level

The receiver shall provide a maximum PER of 10% at a PSDU length of 1000 octets, for a maximum input level of –30 dBm measured at the antenna for any baseband modulation.

18.3.10.6 CCA requirements

CCA shall detect a medium busy condition when the carrier sense/clear channel assessment (CS/CCA) mechanism detects a channel busy condition. For the operating classes requiring CCA-Energy Detect (CCA-ED), CCA shall also detect a medium busy condition when CCA-ED detects a channel busy condition.

The start of a valid OFDM transmission at a receive level equal to or greater than the minimum modulation and coding rate sensitivity (–82 dBm for 20 MHz channel spacing, –85 dBm for 10 MHz channel spacing, and –88 dBm for 5 MHz channel spacing) shall cause CS/CCA to indicate busy with a probability > 90% within 4 µs for 20 MHz channel spacing, 8 µs for 10 MHz channel spacing, and 16 µs for 5 MHz channel spacing. If the preamble portion was missed, the receiver shall hold the CCA signal busy for any signal 20 dB above the minimum modulation and coding rate sensitivity (–62 dBm for 20 MHz channel spacing, –65 dBm for 10 MHz channel spacing, and –68 dBm for 5 MHz channel spacing).

NOTE—CS/CCA detect time is based on finding the short sequences in the preamble, so when T_{SYM} doubles, so does CS/CCA detect time.

For improved spectrum sharing, CCA-ED is required in some bands. The behavior class indicating CCA-ED is given in Table D-2. The operating classes requiring the corresponding CCA-ED behavior class are given in E.1. A STA that is operating within an operating class that requires CCA-ED shall operate with CCA-ED. The CCA-ED shall not be required for license-exempt operation in any band.

CCA-ED shall indicate a channel busy condition when the received signal strength exceeds the CCA-ED threshold as given by dot11OFDMEDThreshold. The CCA-ED thresholds for the operating classes requiring CCA-ED are subject to the criteria in D.2.5.

NOTE—The requirement to hold the CCA signal busy for any signal 20dB above the minimum modulation and coding rate sensitivity (–62 dBm for 20 MHz channel spacing, –65 dBm for 10 MHz channel spacing, and –68 dBm for 5 MHz channel spacing) is a mandatory energy detect requirement on all Clause 18 receivers. Support for CCA-ED is an additional requirement that relates specifically to the sensitivities described in D.2.5.

18.3.10.7 Received Channel Power Indicator Measurement

The RCPI indicator is a measure of the received RF power in the selected channel for a received frame. This parameter shall be a measure by the PHY sublayer of the received RF power in the channel measured over the entire received frame or by other equivalent means that meet the specified accuracy. RCPI shall be a monotonically increasing, logarithmic function of the received power level defined in dBm. The allowed values for the RCPI parameter shall be an 8-bit value in the range from 0 to 220, with indicated values rounded to the nearest 0.5 dB as follows:

0: Power ≤ – 110 dBm

1: Power = – 109.5 dBm

2: Power = – 109.0 dBm

and so on where

$$\text{RCPI} = \text{Int}\{(\text{Power in dBm} + 110) \times 2\} \text{ for } 0 \text{ dBm} > \text{Power} > -110 \text{ dBm}$$

220: Power ≥ – 0 dBm

221–254: Reserved

255: Measurement not available

RCPI shall equal the received RF power within an accuracy of ±5 dB (95% confidence interval) within the specified dynamic range of the receiver. The received RF power shall be determined assuming a receiver noise equivalent bandwidth equal to the channel bandwidth multiplied by 1.1.

18.3.11 Transmit PLCP

The transmit PLCP is shown in Figure 18-17. In order to transmit data, the PHY-TXSTART.request primitive shall be enabled so that the PHY entity shall be in the transmit state. Further, the PHY shall be set to operate at the appropriate frequency through STA management via the PLME. Other transmit parameters, such as DATARATE and TX power, are set via the PHY-SAP with the PHY-TXSTART.request(TXVECTOR) primitive, as described in 18.2.2.

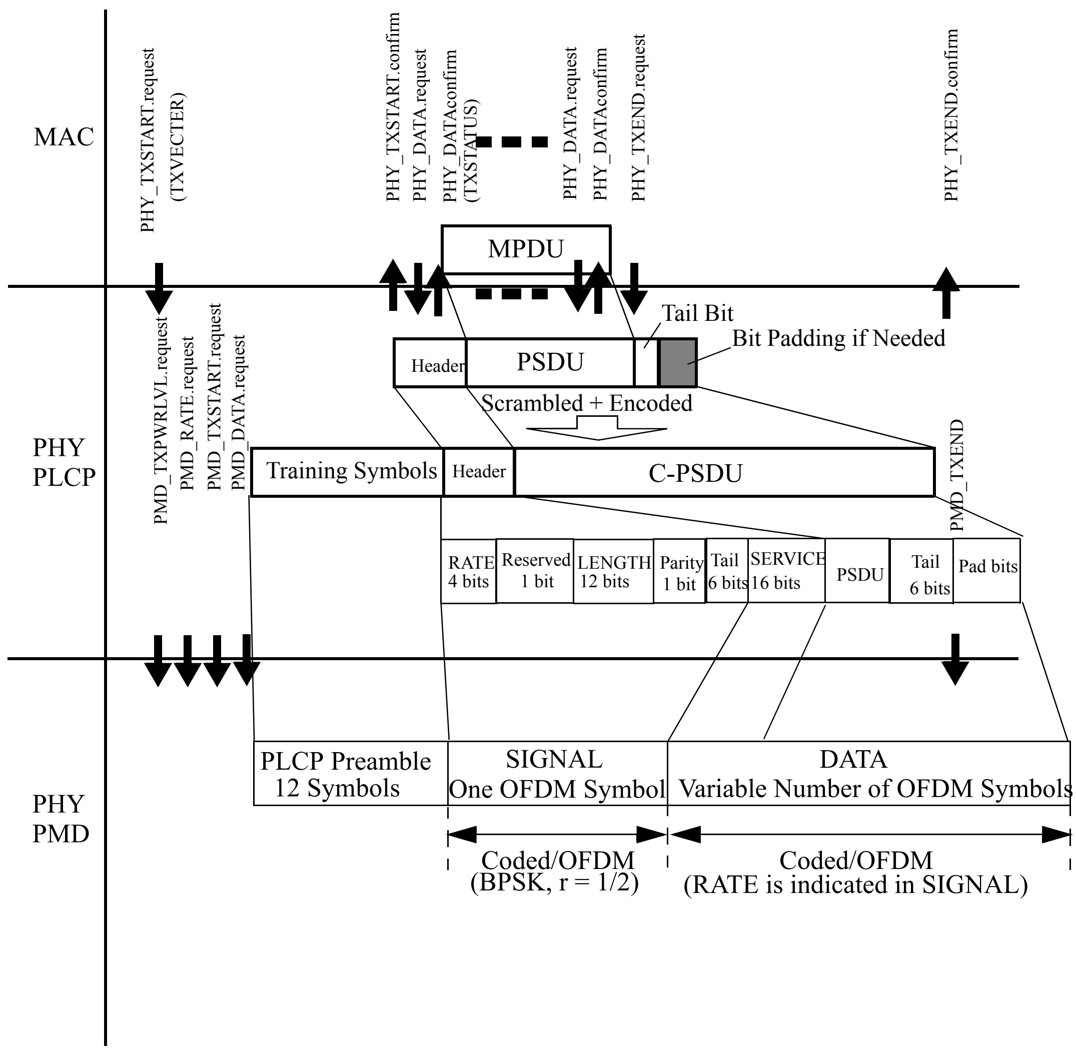

Figure 18-17—Transmit PLCP

A clear channel shall be indicated by a PHY-CCA.indication(IDLE) primitive. The MAC considers this indication before issuing the PHY-TXSTART.request primitive. Transmission of the PPDU shall be initiated after receiving the PHY-TXSTART.request(TXVECTOR) primitive. The TXVECTOR elements for the PHY-TXSTART.request primitive are the PLCP header parameters DATARATE, SERVICE, and LENGTH and the PMD parameters TXPWR_LEVEL and TIME_OF_DEPARTURE_REQUESTED.

The PLCP shall issue PMD_TXPWRLVL and PMD_RATE primitives to configure the PHY. The PLCP shall then issue a PMD_TXSTART.request primitive, and transmission of the PLCP preamble and PLCP header, based on the parameters passed in the PHY-TXSTART.request primitive, shall be immediately initiated. If dot11MgmtOptionTODImplemented and dot11MgmtOptionTODActivated are true or if dot11MgmtOptionTimingMsmtActivated is true and the TXVECTOR parameter TIME_OF_DEPARTURE_REQUESTED is true, then the PLCP shall issue a PHY_TXSTART.confirm(TXSTATUS) primitive to the MAC, forwarding the TIME_OF_DEPARTURE corresponding to the time when the first frame energy is sent by the transmitting port and the TIME_OF_DEPARTURE_ClockRate parameter within the TXSTATUS vector. If dot11MgmtOptionTimingMsmtActivated is true, then the PLCP shall forward the value of TX_START_OF_FRAME_OFFSET in the TXSTATUS vector. Once PLCP preamble transmission is started, the PHY entity shall immediately initiate PLCP header encoding then data scrambling and data encoding, where the data shall be exchanged between the MAC and the PHY through a series of PHY-DATA.request(DATA) primitives issued by the MAC, and PHY-DATA.confirm primitives issued by the PHY. The modulation rate change, if any, shall be initiated from the SERVICE field data of the PLCP header, as described in 18.3.2.

The PHY proceeds with PSDU transmission through a series of data octet transfers from the MAC. The PLCP header parameter, SERVICE, and PSDU are encoded by the convolutional encoder with the bit-stealing function described in 18.3.5.6. At the PMD layer, the data octets are sent in bit 0–7 order and presented to the PHY through PMD_DATA.request primitives. Transmission can be prematurely terminated by the MAC through the PHY-TXEND.request primitive. PHY-TXSTART shall be disabled by the issuance of the PHY-TXEND.request primitive. Normal termination occurs after the transmission of the final bit of the last PSDU octet, according to the number supplied in the OFDM PHY preamble LENGTH field.

The packet transmission shall be completed and the PHY entity shall enter the receive state (i.e., PHY-TXSTART shall be disabled). Each PHY-TXEND.request primitive is acknowledged with a PHY-TXEND.confirm primitive from the PHY. If the coded PSDU (C-PSDU) length is not a multiple of the OFDM symbol length N_{CBPS}, the PSDU is padded prior to scrambling and coding (see 18.3.5.4).

In the PMD, the GI shall be inserted in every OFDM symbol as a countermeasure against severe delay spread.

A typical state machine implementation of the transmit PLCP is provided in Figure 18-18. Requests (.request) and confirmations(.confirm) are issued once with designated states.

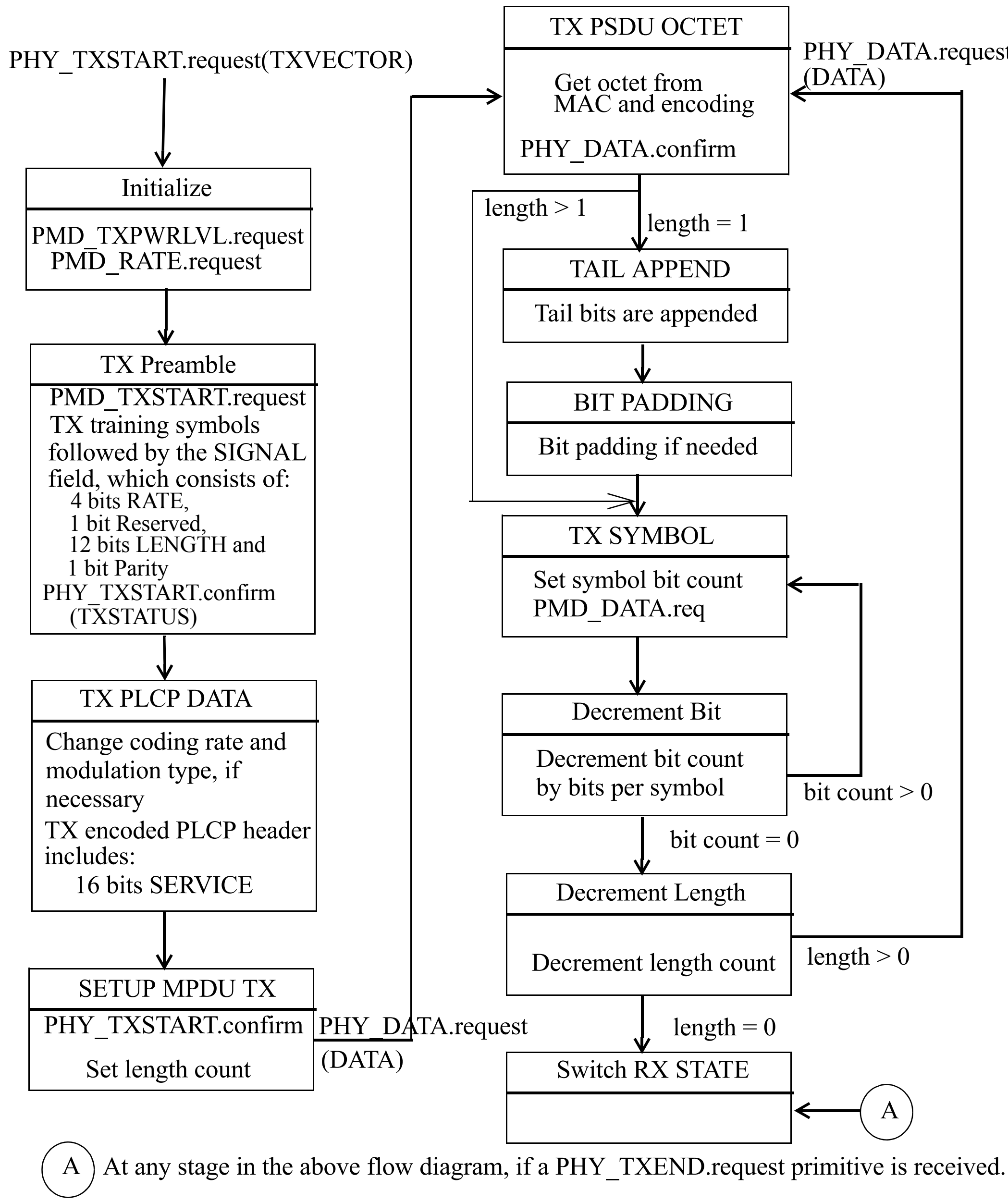

Figure 18-18—PLCP transmit state machine

18.3.12 Receive PLCP

The receive PLCP is shown in Figure 18-19. In order to receive data, the PHY-TXSTART.request primitive shall be disabled so that the PHY entity is in the receive state. Further, through STA management (via the PLME) the PHY is set to the appropriate frequency. Other receive parameters, such as RSSI, RCPI, and indicated DATARATE, may be accessed via the PHY-SAP.

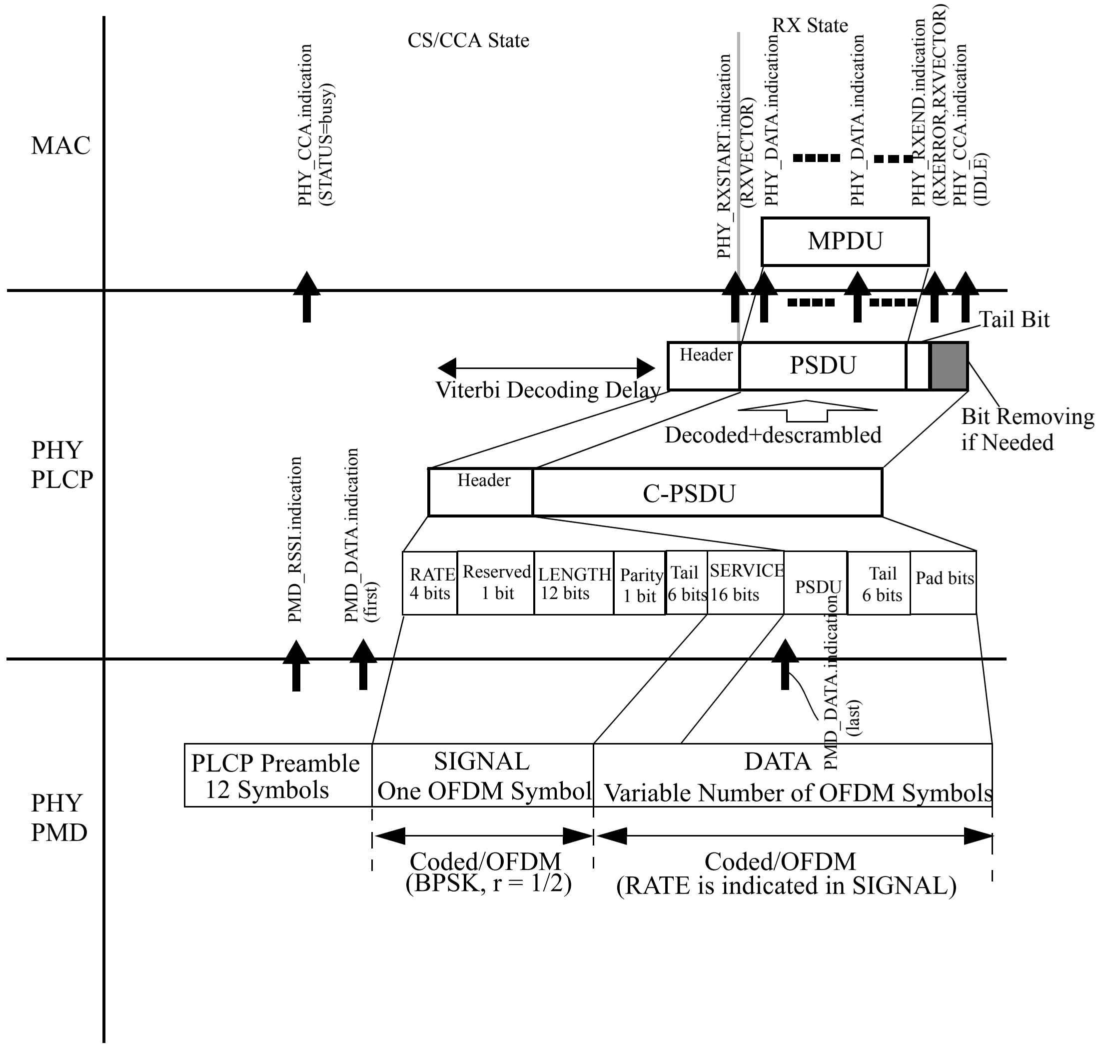

Figure 18-19—Receive PLCP

Upon receiving the transmitted PLCP preamble, a PMD_RSSI.indication primitive shall report a significant received signal strength level to the PLCP. This indicates activity to the MAC via PHY_CCA.indication primitive. A PHY_CCA.indication(BUSY) primitive shall be issued for reception of a signal prior to correct reception of the PLCP frame. The PMD primitive PMD_RSSI is issued to update the RSSI and parameter reported to the MAC.

After a PHY-CCA.indication primitive is issued, the PHY entity shall begin receiving the training symbols and searching for the SIGNAL in order to set the length of the data stream, the demodulation type, and the decoding rate. Once the SIGNAL is detected, without any errors detected by a single parity (even), FEC decode shall be initiated and the PLCP IEEE 802.11 SERVICE fields and data shall be received, decoded (a Viterbi decoder is recommended), and checked by ITU-T CRC-32. If the FCS by the ITU-T CRC-32 check fails, the PHY receiver shall return to the RX IDLE state, as depicted in Figure 18-19. Should the status of CCA return to the IDLE state during reception prior to completion of the full PLCP processing, the PHY receiver shall return to the RX IDLE state.

If the PLCP header reception is successful (and the SIGNAL field is completely recognizable and supported), a PHY-RXSTART.indication(RXVECTOR) primitive shall be issued. If dot11MgmtOptionTimingMsmtActivated is true, the PLCP shall do the following:

— Complete receiving the PLCP header and verify the validity of the PLCP Header.
— If the PLCP header reception is successful (and the SIGNAL field is completely recognizable and supported), a PHY-RXSTART.indication(RXVECTOR) primitive shall be issued and RX_START_OF_FRAME_OFFSET parameter within the RXVECTOR shall be forwarded (see 18.2.3).

NOTE—The RX_START_OF_FRAME_OFFSET value is used as described in 6.3.57 in order to estimate when the start of the preamble for the incoming frame was detected on the medium at the receive antenna port.

The RXVECTOR associated with this primitive includes the SIGNAL field, the SERVICE field, the PSDU length in octets, and the RSSI. Also, in this case, the OFDM PHY shall ensure that the CCA indicates a busy medium for the intended duration of the transmitted frame, as indicated by the LENGTH field.

The received PSDU bits are assembled into octets, decoded, and presented to the MAC using a series of PHY-DATA.indication(DATA) primitive exchanges. The rate change indicated in the IEEE 802.11 SIGNAL field shall be initiated from the SERVICE field data of the PLCP header, as described in 18.3.2. The PHY shall proceed with PSDU reception. After the reception of the final bit of the last PSDU octet indicated by the PLCP preamble LENGTH field, the receiver shall be returned to the RX IDLE state, as shown in Figure 18-19. A PHY-RXEND.indication(NoError) primitive shall be issued.

In the event that a change in the RSSI causes the status of the CCA to return to the IDLE state before the complete reception of the PSDU, as indicated by the PLCP LENGTH field, the error condition shall be reported to the MAC using a PHY-RXEND.indication(CarrierLost) primitive. The OFDM PHY shall ensure that the CCA indicates a busy medium for the intended duration of the transmitted packet.

If the indicated rate in the SIGNAL field is not receivable, a PHY-RXSTART.indication primitive shall not be issued. The PHY shall indicate the error condition using a PHY-RXEND.indication(UnsupportedRate) primitive and hold CCA busy for the calculated duration of the PPDU. If the PLCP header is receivable, but the parity check of the PLCP header is not valid, a PHY-RXSTART.indication primitive shall not be issued. The PHY shall indicate the error condition using a PHY-RXEND.indication(FormatViolation) primitive.

Any data received after the indicated data length are considered pad bits (to fill out an OFDM symbol) and should be discarded.

A typical state machine implementation of the receive PLCP is given in Figure 18-20.

18.4 OFDM PLME

18.4.1 PLME_SAP sublayer management primitives

Table 18-16 lists the MIB attributes that may be accessed by the PHY entities and the intralayer of higher level LMEs. These attributes are accessed via the PLME-GET, PLME-SET, PLME-RESET, and PLME-CHARACTERISTICS primitives defined in 6.5.

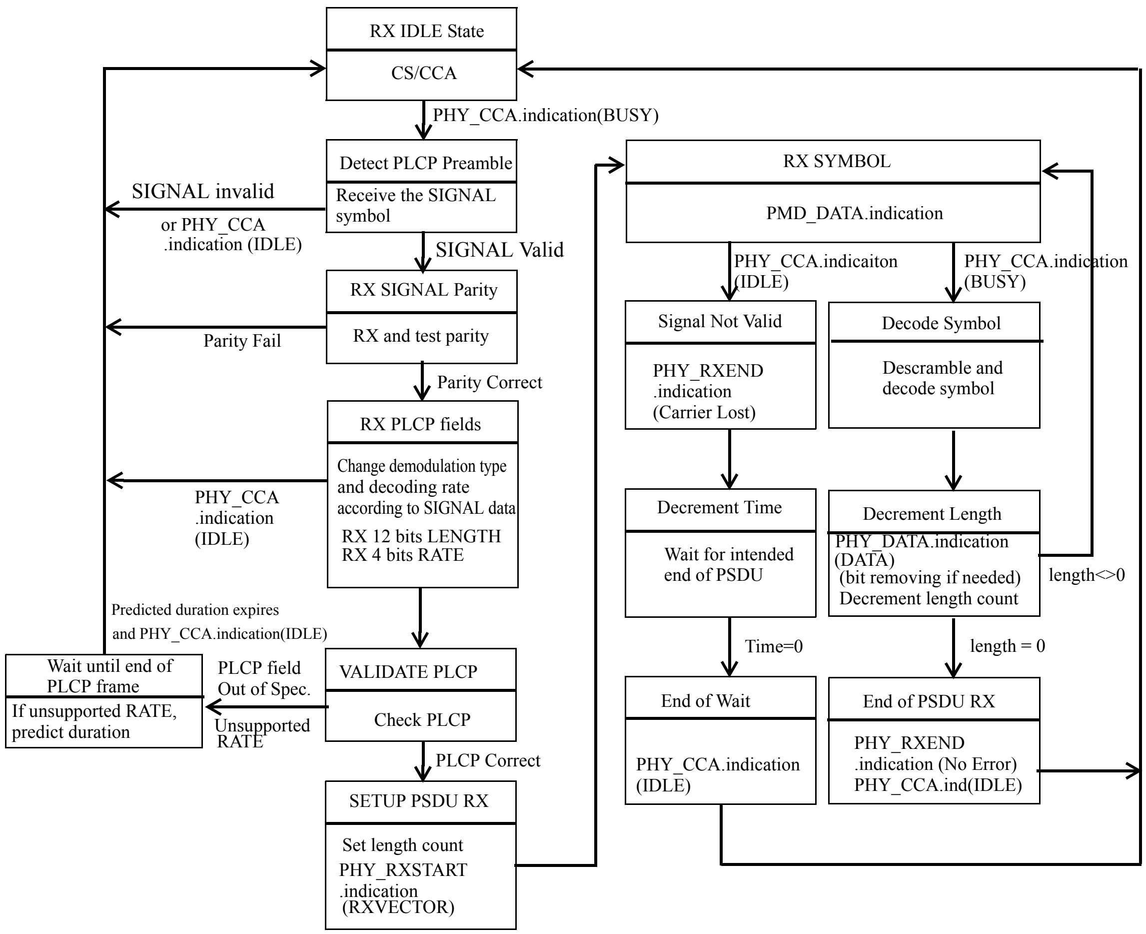

Figure 18-20—PLCP receive state machine

18.4.2 OFDM PHY MIB

All OFDM PHY MIB attributes are defined in Annex C, with specific values defined in Table 18-16. The column titled “Operational semantics” in Table 18-16 contains two types: static and dynamic. Static MIB attributes are fixed and cannot be modified for a given PHY implementation. Dynamic MIB attributes can be modified by some management entity.

Table 18-16—MIB attribute default values/ranges

Managed object	Default value/range	Operational semantics
dot11 PHY Operation Table		
dot11PHYtype	OFDM-5. (04)	Static
dot11CurrentRegDomain	Implementation dependent	Dynamic
dot11CurrentFrequencyBand	Implementation dependent	Dynamic

Table 18-16—MIB attribute default values/ranges *(continued)*

Managed object	Default value/range	Operational semantics
dot11 PHY Antenna Table		
dot11CurrentTxAntenna	Implementation dependent	Dynamic
dot11DiversitySupportImplemented	Implementation dependent	Static
dot11CurrentRxAntenna	Implementation dependent	Dynamic
dot11 PHY Tx Power Table		
dot11NumberSupportedPowerLevelsImplemented	Implementation dependent	Static
dot11TxPowerLevel1	Implementation dependent	Static
dot11TxPowerLevel2	Implementation dependent	Static
dot11TxPowerLevel3	Implementation dependent	Static
dot11TxPowerLevel4	Implementation dependent	Static
dot11TxPowerLevel5	Implementation dependent	Static
dot11TxPowerLevel6	Implementation dependent	Static
dot11TxPowerLevel7	Implementation dependent	Static
dot11TxPowerLevel8	Implementation dependent	Static
dot11CurrentTxPowerLevel	Implementation dependent	Dynamic
dot11 Reg Domains Supported Table		
dot11RegDomainsImplementedValue	Implementation dependent	Static
dot11FrequencyBandsSupported	Implementation dependent	Static
dot11 PHY Antennas List Table		
dot11SupportedTxAntenna	Implementation dependent	Static
dot11SupportedRxAntenna	Implementation dependent	Static
dot11DiversitySelectionRx	Implementation dependent	Dynamic
dot11 Supported Data Rates Tx Table		
dot11ImplementedDataRatesTxValue	6, 9, 12, 18, 24, 36, 48, and 54 Mb/s for 20 MHz channel spacing (Mandatory rates: 6, 12, and 24) 3, 4.5, 6, 9, 12, 18, 24, and 27 Mb/s for 10 MHz channel spacing (Mandatory rates: 3, 6, and 12) 1.5, 2.25, 3, 4.5, 6, 9, 12, and 13.5 Mb/s for 5 MHz channel spacing (Mandatory rates: 1.5, 3, and 6)	Static

Table 18-16—MIB attribute default values/ranges *(continued)*

Managed object	Default value/range	Operational semantics
dot11 Supported Data Rates Rx Table		
dot11ImplementedDataRatesRxValue	6, 9, 12, 18, 24, 36, 48, and 54 Mb/s for 20 MHz channel spacing (Mandatory rates: 6, 12, and 24) 3, 4.5, 6, 9, 12, 18, 24, and 27 Mb/s for 10 MHz channel spacing (Mandatory rates: 3, 6, and 12) 1.5, 2.25, 3, 4.5, 6, 9, 12, and 13.5 Mb/s for 5 MHz channel spacing (Mandatory rates: 1.5, 3, and 6)	Static
dot11 PHY OFDM Table		
dot11CurrentFrequency	Implementation dependent	Dynamic
dot11TIThreshold	Implementation dependent	Dynamic
dot11ChannelStartingFactor	Implementation dependent	Dynamic
dot11OFDMEDThreshold	Implementation dependent	Dynamic
dot11ACRType	Implementation dependent	Dynamic

18.4.3 OFDM TXTIME calculation

The value of the TXTIME parameter returned by the PLME-TXTIME.confirm primitive shall be calculated according to the following equation:

$$\mathrm{TXTIME} = T_{PREAMBLE} + T_{SIGNAL} + T_{SYM} \times N_{SYM} \tag{18-29}$$

where

$T_{PREAMBLE}$ is defined in Table 18-5
T_{SIGNAL} is defined in Table 18-5
T_{SYM} is defined in Table 18-5
N_{SYM} is given by Equation (18-11).

18.4.4 OFDM PHY characteristics

The static OFDM PHY characteristics, provided through the PLME-CHARACTERISTICS service primitive, are shown in Table 18-17. The definitions for these characteristics are given in 6.5.

Table 18-17—OFDM PHY characteristics

Characteristics	Value (20 MHz channel spacing)	Value (10 MHz channel spacing)	Value (5 MHz channel spacing)
aSlotTime	9 µs	13 µs	21 µs
aSIFSTime	16 µs	32 µs	64 µs
aCCATime	< 4 µs	< 8 µs	< 16 µs
aPHY-RX-START-Delay	25 µs	49 µs	97 µs
aRxTxTurnaroundTime	< 2 µs	< 2 µs	< 2 µs
aTxPLCPDelay	Implementation dependent as long as the requirements of aRxTxTurnaroundTime are met.	Implementation dependent as long as the requirements of aRxTxTurnaroundTime are met.	Implementation dependent as long as the requirements of aRxTxTurnaroundTime are met.
aRxPLCPDelay	Implementation dependent as long as the requirements of aSIFSTime and aCCATime are met.	Implementation dependent as long as the requirements of aSIFSTime and aCCATime are met.	Implementation dependent as long as the requirements of aSIFSTime and aCCATime are met.
aRxTxSwitchTime	<< 1 µs	<< 1 µs	<< 1 µs
aTxRampOnTime	Implementation dependent as long as the requirements of aRxTxTurnaroundTime are met.	Implementation dependent as long as the requirements of aRxTxTurnaroundTime are met.	Implementation dependent as long as the requirements of aRxTxTurnaroundTime are met.
aTxRampOffTime	Implementation dependent as long as the requirements of aSIFSTime are met.	Implementation dependent as long as the requirements of aSIFSTime are met.	Implementation dependent as long as the requirements of aSIFSTime are met.
aTxRFDelay	Implementation dependent as long as the requirements of aRxTxTurnaroundTime are met.	Implementation dependent as long as the requirements of aRxTxTurnaroundTime are met.	Implementation dependent as long as the requirements of aRxTxTurnaroundTime are met.
aRxRFDelay	Implementation dependent as long as the requirements of aSIFSTime and aCCATime are met.	Implementation dependent as long as the requirements of aSIFSTime and aCCATime are met.	Implementation dependent as long as the requirements of aSIFSTime and aCCATime are met.
aAirPropagationTime	<< 1 µs	<< 1 µs	<< 1 µs
aMACProcessingDelay	< 2 µs	< 2 µs	< 2 µs
aPreambleLength	16 µs	32 µs	64 µs
aPLCPHeaderLength	4 µs	8 µs	16 µs
aMPDUMaxLength	4095	4095	4095
aCWmin	15	15	15
aCWmax	1023	1023	1023

18.5 OFDM PMD sublayer

18.5.1 Scope and field of application

Subclause 18.5 describes the PMD services provided to the PLCP for the OFDM PHY. Also defined in 18.5 are the functional, electrical, and RF characteristics required for interoperability of implementations conforming to this specification. The relationship of this specification to the entire OFDM PHY is shown in Figure 18-21.

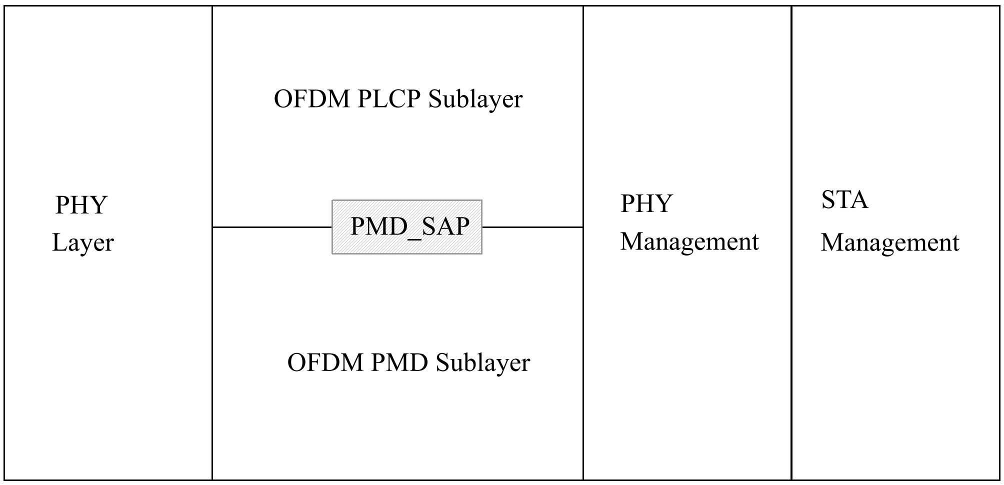

Figure 18-21—PMD layer reference model

18.5.2 Overview of service

The OFDM PMD sublayer accepts PLCP sublayer service primitives and provides the actual means by which data are transmitted or received from the medium. The combined function of the OFDM PMD sublayer primitives and parameters for the receive function results in a data stream, timing information, and associated receive signal parameters being delivered to the PLCP sublayer. A similar functionality shall be provided for data transmission.

18.5.3 Overview of interactions

The primitives associated with the IEEE 802.11 PLCP sublayer to the OFDM PMD fall into two basic categories:

a) Service primitives that support PLCP peer-to-peer interactions;
b) Service primitives that have local significance and support sublayer-to-sublayer interactions.

18.5.4 Basic service and options

18.5.4.1 General

All of the service primitives described in 18.5.4 are considered mandatory, unless otherwise specified.

18.5.4.2 PMD_SAP peer-to-peer service primitives

Table 18-18 indicates the primitives for peer-to-peer interactions.

Table 18-18—PMD_SAP peer-to-peer service primitives

Primitive	Request	Indicate	Confirm	Response
PMD_DATA	X	X	—	—

18.5.4.3 PMD_SAP sublayer-to-sublayer service primitives

Table 18-19 indicates the primitives for sublayer-to-sublayer interactions.

Table 18-19—PMD_SAP sublayer-to-sublayer service primitives

Primitive	Request	Indicate	Confirm	Response
PMD_TXSTART	X	—	—	—
PMD_TXEND	X	—	—	—
PMD_TXPWRLVL	X	—	—	—
PMD_RATE	X	—	—	—
PMD_RSSI	—	X	—	—
PMD_RCPI	—	X	—	—

18.5.4.4 PMD_SAP service primitive parameters

Table 18-20 shows the parameters used by one or more of the PMD_SAP service primitives.

Table 18-20—List of parameters for the PMD primitives

Parameter	Associated primitive	Value (20 MHz channel spacing)	Value (10 MHz channel spacing)	Value (5 MHz channel spacing)
TXD_UNIT	PMD_DATA.request	One(1), Zero(0): one OFDM symbol value	One(1),Zero(0): one OFDM symbol value	One(1),Zero(0): one OFDM symbol value
RXD_UNIT	PMD_DATA. indication	One(1), Zero(0): one OFDM symbol value	One(1),Zero(0): one OFDM symbol value	One(1),Zero(0): one OFDM symbol value
TXPWR_LEVEL	PMD_TXPWRLVL. request	1–8 (max of 8 levels)	1–8 (max of 8 levels)	1–8 (max of 8 levels)
RATE	PMD_RATE.request	12 Mb/s (for BPSK) 24 Mb/s (for QPSK) 48 Mb/s (for 16-QAM) 72 Mb/s (for 64-QAM)	6 Mb/s (for BPSK) 12 Mb/s (for QPSK) 24 Mb/s (for 16-QAM) 36 Mb/s (for 64-QAM)	3 Mb/s (for BPSK) 6 Mb/s (for QPSK) 12Mb/s (for 16-QAM) 18 Mb/s (for 64-QAM)

Table 18-20—List of parameters for the PMD primitives *(continued)*

Parameter	Associated primitive	Value (20 MHz channel spacing)	Value (10 MHz channel spacing)	Value (5 MHz channel spacing)
RSSI	PMD_RSSI. indication	0–8 bits of RSSI	0–8 bits of RSSI	0–8 bits of RSSI
RCPI	PMD_RCPI. indication	0–255	0–255	0–255

18.5.5 PMD_SAP detailed service specification

18.5.5.1 Introduction

Subclause 18.5.5 describes the services provided by each PMD primitive.

18.5.5.2 PMD_DATA.request

18.5.5.2.1 Function

This primitive defines the transfer of data from the PLCP sublayer to the PMD entity.

18.5.5.2.2 Semantics of the service primitive

This primitive shall provide the following parameter:

```
PMD_DATA.request(
                TXD_UNIT
                )
```

The TXD_UNIT parameter shall be the n-bit combination of 0 and 1 for one symbol of OFDM modulation. If the length of a coded MPDU (C-MPDU) is shorter than n bits, 0 bits are added to form an OFDM symbol. This parameter represents a single block of data which, in turn, shall be used by the PHY to be encoded into an OFDM transmitted symbol.

18.5.5.2.3 When generated

This primitive shall be generated by the PLCP sublayer to request transmission of one OFDM symbol. The data clock for this primitive shall be supplied by the PMD layer based on the OFDM symbol clock.

18.5.5.2.4 Effect of receipt

The PMD performs transmission of the data.

18.5.5.3 PMD_DATA.indication

18.5.5.3.1 Function

This primitive defines the transfer of data from the PMD entity to the PLCP sublayer.

18.5.5.3.2 Semantics of the service primitive

This primitive shall provide the following parameter:

PMD_DATA.indication(
RXD_UNIT
)

The RXD_UNIT parameter shall be 0 or 1, and shall represent either a signal field bit or a data field bit after the decoding of the convolutional code by the PMD entity.

18.5.5.3.3 When generated

This primitive, generated by the PMD entity, forwards received data to the PLCP sublayer. The data clock for this primitive shall be supplied by the PMD layer based on the OFDM symbol clock.

18.5.5.3.4 Effect of receipt

The PLCP sublayer interprets the bits that are recovered as part of the PLCP or passes the data to the MAC sublayer as part of the MPDU.

18.5.5.4 PMD_TXSTART.request

18.5.5.4.1 Function

This primitive, generated by the PHY PLCP sublayer, initiates PPDU transmission by the PMD layer.

18.5.5.4.2 Semantics of the service primitive

The semantics of this primitive are as follows:

PMD_TXSTART.request

18.5.5.4.3 When generated

This primitive shall be generated by the PLCP sublayer to initiate the PMD layer transmission of the PPDU. The PHY-TXSTART.request primitive shall be provided to the PLCP sublayer prior to issuing the PMD_TXSTART command.

18.5.5.4.4 Effect of receipt

PMD_TXSTART initiates transmission of a PPDU by the PMD sublayer.

18.5.5.5 PMD_TXEND.request

18.5.5.5.1 Function

This primitive, generated by the PHY PLCP sublayer, ends PPDU transmission by the PMD layer.

18.5.5.5.2 Semantics of the service primitive

The semantics of this primitive are as follows:

PMD_TXEND.request

18.5.5.5.3 When generated

This primitive shall be generated by the PLCP sublayer to terminate the PMD layer transmission of the PPDU.

18.5.5.5.4 Effect of receipt

PMD_TXEND terminates transmission of a PPDU by the PMD sublayer.

18.5.5.6 PMD_TXPWRLVL.request

18.5.5.6.1 Function

This primitive, generated by the PHY PLCP sublayer, selects the power level used by the PHY for transmission.

18.5.5.6.2 Semantics of the service primitive

This primitive shall provide the following parameter:

```
PMD_TXPWRLVL.request(
                        TXPWR_LEVEL
                        )
```

TXPWR_LEVEL selects which of the transmit power levels should be used for the current packet transmission. The number of available power levels shall be determined by the MIB parameter aNumberSupportedPowerLevels. See 18.3.9.2 for further information on the OFDM PHY power level control capabilities.

18.5.5.6.3 When generated

This primitive shall be generated by the PLCP sublayer to select a specific transmit power. This primitive shall be applied prior to setting PMD_TXSTART into the transmit state.

18.5.5.6.4 Effect of receipt

PMD_TXPWRLVL immediately sets the transmit power level to that given by TXPWR_LEVEL.

18.5.5.7 PMD_RATE.request

18.5.5.7.1 Function

This primitive, generated by the PHY PLCP sublayer, selects the modulation rate that shall be used by the OFDM PHY for transmission.

18.5.5.7.2 Semantics of the service primitive

This primitive shall provide the following parameter:

```
PMD_RATE.request(
                        RATE
                        )
```

RATE selects which of the OFDM PHY data rates shall be used for MPDU transmission. See 18.3.8.7 for further information on the OFDM PHY modulation rates. The OFDM PHY rate change capability is described in detail in 18.3.7.

18.5.5.7.3 When generated

This primitive shall be generated by the PLCP sublayer to change or set the current OFDM PHY modulation rate used for the MPDU portion of a PPDU.

18.5.5.7.4 Effect of receipt

The receipt of PMD_RATE selects the rate that shall be used for all subsequent MPDU transmissions. This rate shall be used for transmission only. The OFDM PHY shall still be capable of receiving all the required OFDM PHY modulation rates.

18.5.5.8 PMD_RSSI.indication

18.5.5.8.1 Function

This primitive, generated by the PMD sublayer, provides the receive signal strength to the PLCP and MAC entity.

18.5.5.8.2 Semantics of the service primitive

This primitive shall provide the following parameter:

```
PMD_RSSI.indication(
                    RSSI
                    )
```

The RSSI shall be a measure of the RF energy received by the OFDM PHY. RSSIs of up to 8 bits (256 levels) are supported.

18.5.5.8.3 When generated

This primitive shall be generated by the PMD when the OFDM PHY is in the receive state. It shall be available continuously to the PLCP which, in turn, shall provide the parameter to the MAC entity.

18.5.5.8.4 Effect of receipt

This parameter shall be provided to the PLCP layer for information only. The RSSI may be used as part of a CCA scheme.

18.5.5.9 PMD_RCPI.indication

18.5.5.9.1 Function

This primitive, generated by the PMD sublayer, provides the RCPI to the PLCP and MAC entity.

18.5.5.9.2 Semantics of the service primitive

The primitive shall provide the following parameter:

```
PMD_RCPI.indication(
                    RCPI
                    )
```

The RCPI shall be a measure of the channel power received by the OFDM PHY. RCPI indications of 8 bits are supported, as defined in 18.3.10.7.

18.5.5.9.3 When generated

This primitive shall be generated by the PMD when the OFDM PHY is in the receive state. It shall be continuously available to the PLCP, which in turn provides the parameter to the MAC entity.

18.5.5.9.4 Effect of receipt

This parameter shall be provided to the PLCP layer for information only. The RCPI may be used in conjunction with RSSI to measure input signal quality.

