OFDM Physical Layer Specification for the 5 GHz Band

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Abstract
This paper describes the OFDM proposal for the 5 GHz band in a format which is similar to the format of the existing 802.11 direct-sequence spread-spectrum standard for the 2.4 GHz band.

1.1 Introduction

This clause describes the physical layer for the Orthogonal Frequency Division Multiplex (OFDM) system. The Radio Frequency LAN system is initially aimed for the 5 GHz NII band.

The OFDM system provides a wireless LAN with data payload communication capabilities of 5, 10, 20 and 30 Mbit/s. The system uses 48 subcarriers which are modulated using Binary or Quadrature Phase Shift Keying (BPSK/QPSK), or 16-Quadrature Amplitude Modulation (16-QAM). Forward error correction coding is used with a coding rate of ½ or ¾.

1.1.1 Scope

This clause describes the physical layer services provided to the 802.11 wireless LAN MAC by the 5 GHz OFDM system. The OFDM PHY layer consists of two protocol functions:

a) A physical layer convergence function which adapts the capabilities of the physical medium dependent system to the Physical Layer service. This function shall be supported by the Physical Layer Convergence Procedure (PLCP) which defines a method of mapping the 802.11 MAC sublayer Protocol Data Units (MPDU) into a framing format suitable for sending and receiving user data and management information between two or more stations using the associated physical medium dependent system.
b) A Physical Medium Dependent (PMD) system whose function defines the characteristics and method of transmitting and receiving data through a wireless medium between two or more stations each using the OFDM system.

1.1.2 OFDM Physical Layer Functions

The OFDM physical layer contains three functional entities: the physical medium dependent function, the physical layer convergence function, and the layer management function. Each of these functions is described in detail in the following subclauses.

1.1.2.1 Physical Layer Convergence Procedure Sublayer

In order to allow the 802.11 MAC to operate with minimum dependence on the PMD sublayer, a physical layer convergence sublayer is defined. This function simplifies the physical layer service interface to the 802.11 MAC services.

1.1.2.2 Physical Medium Dependent Sublayer

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

1.1.2.3 Physical Layer Management Entity (LME)

The Physical LME performs management of the local Physical Layer Functions in conjunction with the MAC Management entity.

1.1.3 Service Specification Method and Notation

The models represented by figures and state diagrams are intended to be illustrations of 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 802.11 OFDM PHY compliant developer.

The service of a layer or sublayer is a 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.

1.2 OFDM Physical Layer Convergence Procedure Sublayer

1.2.1 Introduction

This clause provides a convergence procedure in which MPDUs are converted to and from PPDUs. During transmission, the MPDU shall be prepended 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 MPDU.

1.2.2 Physical Layer Convergence Procedure Frame Format

Figure 1 shows the format for the PPDU including the OFDM PLCP preamble, the OFDM PLCP header and the MPDU. The PLCP preamble contains the Synchronization (SYNC). The PLCP header contains the following fields: signaling (SIGNAL), service (SERVICE), length (LENGTH), and CCITT CRC-16. Each of these fields is described in detail in clause 1.2.3.

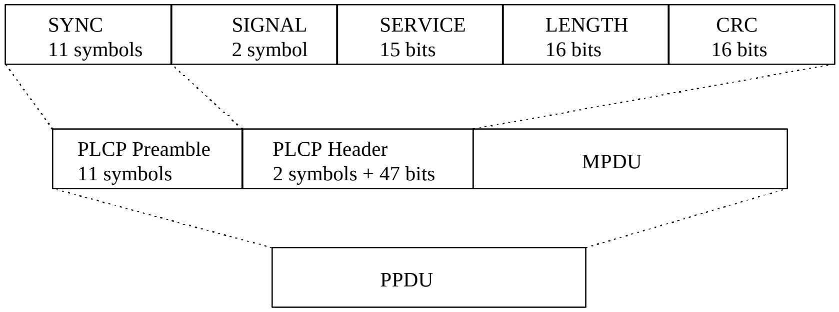

Figure 1, PLCP Frame Format

1.2.3 PLCP Field Definitions

1.2.3.1 PLCP Synchronization (SYNC)

The synchronization field consists of short and long OFDM training symbols.

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

$$S=\{1\ j\ 1\ -1\ -1\ 1\ -1\ -j\ -1\ -1\ -1\ 1\} \tag{1}$$

For one short training symbol starting at $t=t_s$, the signal can be written as:

$$r_t(t) = \mathrm{Re}\left\{ w_t(t-t_s) \sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} S_{i+\frac{N_s}{2}} \exp\left(j2\pi\left(f_c - \frac{i+0.5}{T_t}\right)\left(t - t_s - \frac{\beta T_t}{2}\right)\right) \right\} \ , \ t_s \le t \le t_s + T_t + \beta T \tag{2}$$

$$r_t(t) = 0\ ,\ t<t_s\ \wedge\ t>t_s + T_t + \beta T$$

The symbol interval T_t is exactly ¼ of the FFT duration *T* of a data symbol, which is equal to ((64/76)/4) · 4.8 µs, or approximately 1.01 µs.

The training symbols are windowed by the window function $w_t(t)$ to ensure a sharp spectrum roll-off outside the band.

$$w_t(t) = \begin{cases} 0.5 + 0.5\cos\left(\pi + \dfrac{t\pi}{\beta T}\right) & 0 \le t \le \beta T \\ 1.0 & \beta T \le t \le T_t \\ 0.5 + 0.5\cos\left(\dfrac{(t - T_t)\pi}{\beta T}\right) & T_t \le t \le T_t + \beta T \end{cases} \tag{3}$$

A long OFDM training symbol consists of 48 subcarriers, which are phase modulated by the elements of the sequence *K*, given by:

$$K = \{1\ j\ 1\ 1\ 1\ -1\ 1\ j\ 1\ -1\ -1\ 1\ 1\ j\ 1\ 1\ 1\ -1\ -1\ -j\ -1\ 1\ 1\ -1\ 1\ j\ 1\ 1\ 1\ -1\ 1\ j\ 1\ -1\ -1\ 1\ -1\ -j\ -1\ -1\ -1\ 1\ 1\ j\ 1\ -1\ -1\ 1\} \tag{4}$$

The 48 elements of K are used to phase rotate 48 OFDM subcarriers. A long OFDM training symbol can be written in the same way as an OFDM data symbol (6), with d_i replaced by $K_{i+Ns/2}$.

Figure 2 shows the OFDM training structure, where t_1 to t_{11} denote short training symbols and T1 and T2 are long training symbols. The total training length is 21 µs, including the SIGNAL field, which indicates the type of coding and modulation used in the OFDM data symbols.

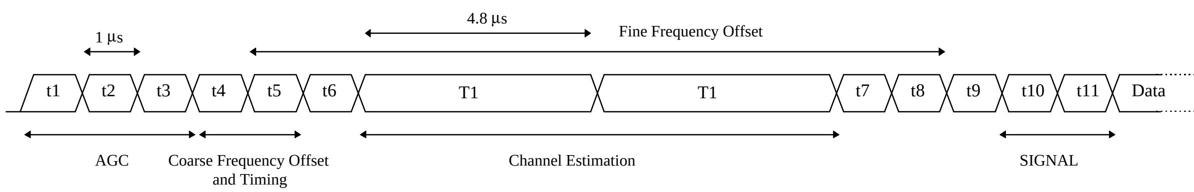

Figure 2, Training Structure

1.2.3.2 Signal Field (SIGNAL)

At the end of the OFDM training, two short OFDM training symbols are sent which contain information about the type of modulation and the coding rate as used in the rest of the packet. A total of 4 bits are encoded by using QPSK on the entire short training symbol, so all subcarriers are modulated by the same phase. Table 1 lists the contents of the Signal field, with the corresponding QPSK phases between brackets.

Bit	Content
1,2	00 (0) = BPSK, 01 (π/2) = QPSK, 10 (π) = 16-QAM, 11 (3π/2) = 64-QAM
3,4	00 = no coding, 01 = rate ½, 10 = rate ¾, 11 = not used

Table 1, Contents of Signal Field

1.2.3.3 PLCP 802.11 Service Field (SERVICE)

The first 7 bits of the service field are used to synchronize the descrambler. The remaining 8 bit 802.11 service field shall be reserved for future use. The value of 00h signifies 802.11 device compliance. The LSB shall be transmitted first in time. This field shall be protected by the CCITT CRC-16 frame check sequence described in clause 1.2.3.5.

1.2.3.4 PLCP Length Field (LENGTH)

The PLCP length field shall be an unsigned 16 bit integer which indicates the number of microseconds (16 to 2^{16}-1 as defined by aMPDUMaxLngth) required to transmit the MPDU. The transmitted value shall be determined from the LENGTH parameter in the TXVECTOR issued with the PHY-TXSTART.request primitive. The length field provided in the TXVECTOR is in bytes and is converted to microseconds for inclusion in the PLCP LENGTH field. The LSB (least significant bit) shall be transmitted first in time. This field shall be protected by the CCITT CRC-16 frame check sequence described in clause 1.2.3.5.

1.2.3.5 PLCP CRC Field (CCITT CRC-16)

The 802.11 SERVICE and LENGTH fields shall be protected with a CCITT CRC-16 FCS (frame check sequence). The CCITT CRC-16 FCS shall be the ones complement of the remainder generated by the modulo 2 division of the protected PLCP fields by the polynomial:

$$x^{16} + x^{12} + x^5 + 1$$

The protected bits shall be processed in transmit order. All FCS calculations shall be made prior to data scrambling.

1.2.4 PLCP / OFDM PHY Data Scrambler and Descrambler

The polynomial $G(z) = z^{-7} + z^{-4} + 1$ shall be used to scramble all bits transmitted by the OFDM PHY, starting from the SERVICE field in the PLCP header. The feedthrough configuration of the scrambler and descrambler is self synchronizing which requires no prior knowledge of the transmitter initialization of the scrambler for receive processing. Figure 3 and Figure 4 show typical implementations of the data scrambler and descrambler. Other implementations are possible.

The scrambler should be initialized to any state except all ones when transmitting. The first 7 output bits are used at the receiver to synchronize the descrambler.

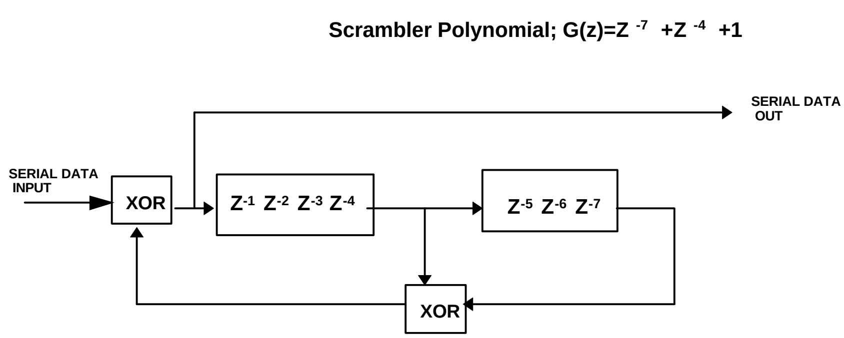

Figure 3, Data Scrambler

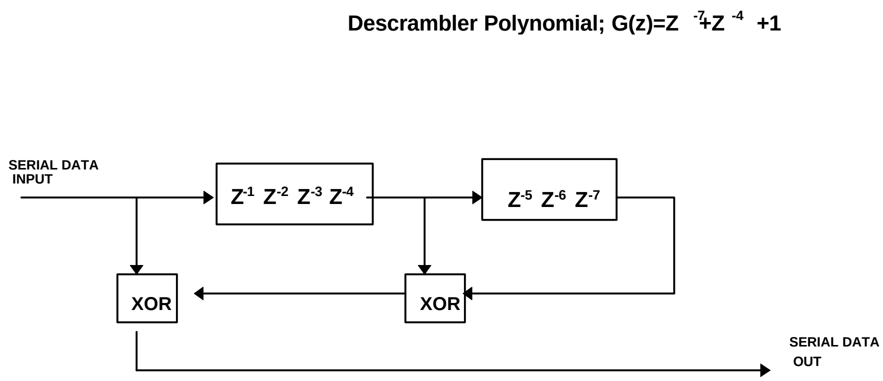

Figure 4, Data Descrambler

1.2.5 Data Interleaving

All data bits shall be interleaved with an interleaving depth of one OFDM symbol. This means that the interleaving depth is 48, 96 or 192 bits for BPSK, QPSK and 16-QAM, respectively. For the various interleaving depths d, the ith interleaved bit is equal to the kth input bit, where k is given by:

$$k=8i-(d-1)\text{floor}(8i/d) \tag{5}$$

1.3 OFDM Physical Medium Dependent Sublayer

1.3.1 Overview of Service

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

1.3.2 PMD Operating Specifications General

The following clauses provide general specifications for the OFDM Physical Medium Dependent sublayer. These specifications apply to both the receive and the transmit functions and general operation of an OFDM PHY.

1.3.2.1 Operating Frequency Range

The OFDM PHY shall operate in the 5 GHz band as allocated by regulatory bodies in the USA and Europe.

1.3.2.2 Channelization

Figure 5 shows a channelization scheme for a total bandwidth of 100 MHz. Five channels can be accomodated for an out-of-band spectral density that is at least 40 dB below the maximum in-band spectral density. If the out-of-band radiation is required to be 50 dB below the in-band density, then the total bandwidth has to be increased to 110 MHz. If a total bandwidth of 200 MHz is available, then 11 channels can be accomodated with 17.5 MHz guard bands at the edges.

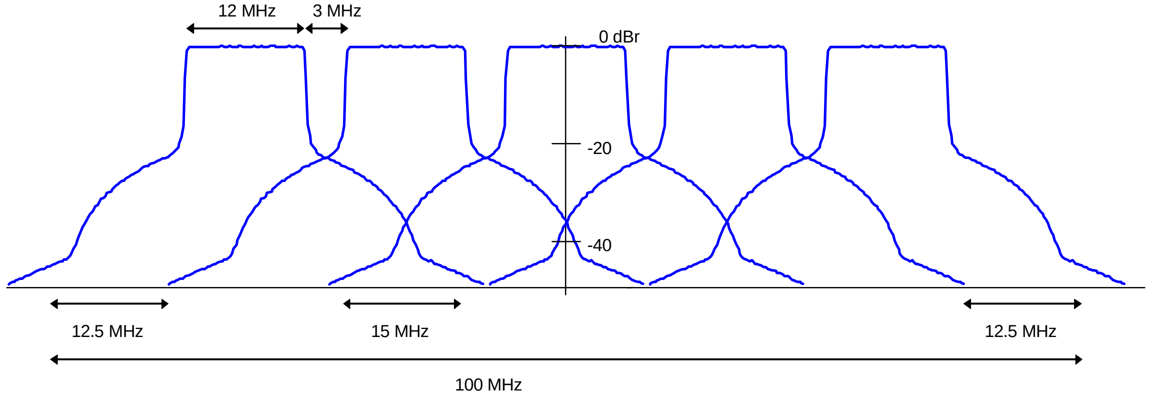

Figure 5, Channelization.

1.3.2.3 Forward Error Correction Coding

For the forward error correction coding, a rate ½, contraint length 7 convolutional code is used. Encoding is performed according to Figure 6, where the 'T_b' blocks denote delays of one bit clock cycle and the adders operate modulo 2. The two output data streams A and B are interleaved, so the output data is $\{A_1B_1A_2B_2\ldots\}$. The first valid output is obtained after the first input bit passed the entire shift register, i.e., after 6 clock cycles. At the end of each input data sequence, 6 zero tail bits have to be added.

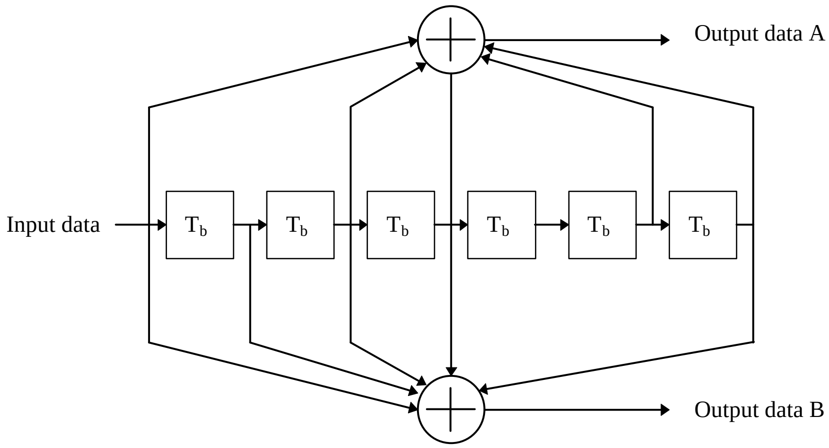

Figure 6, Block diagram of convolutional encoder.

The rate ½ code can be punctured to increase the coding rate to ¾. This is done by deleting 2 of every 6 bits at the output of the rate ½ encoder. The punctured output sequence is: $\{A_1B_1A_2B_3A_4B_4A_5B_6A_7B_7\ldots\}$.

1.3.2.4 Modulation

The OFDM subcarriers can be modulated by using phase shift keying or quadrature amplitude modulation. Binary input data is converted into BPSK, QPSK, or 16-QAM, according to Gray code mappings, which are listed in the following tables:

Input data	I-out	Q-out
1	1	0
0	1	0

Table 2, BPSK Encoding Table

Input data	I-out	Q-out
11	1	1
10	1	-1
01	-1	1
00	-1	-1

Table 3, QPSK Encoding Table

Input data	I-out	Q-out
1010	3	3
1011	3	1
1001	3	-1
1000	3	-3
1110	1	3
1111	1	1
1101	1	-1
1100	1	-3
0110	-1	3
0111	-1	1
0101	-1	-1
0100	-1	-3
0010	-3	3
0011	-3	1
0001	-3	-1
0000	-3	-3

Table 4, 16-QAM Encoding Table

Notice the I/Q values are not normalized; in practice, all mappings should have the same average power, which is possible by dividing all values by the average constellation power. This average power is given in Table 5.

BPSK	1
QPSK	√2
16-QAM	√10

Table 5, Average Power of Constellations

Starting at time $t=t_s$, an OFDM symbol $r_k(t)$ is defined as:

$$r_k(t) = \mathrm{Re}\left\{ w(t-t_s) \sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s(k+1/2)} \exp\left(j2\pi\left(f_c - \frac{i+0.5}{T}\right)(t-t_s-T_{prefix})\right) \right\} \quad , \quad t_s \le t \le t_s + T + T_{prefix} + T_{postfix}$$

$$r_k(t) = 0 \;, \quad t < t_s \;\wedge\; t > t_s + T + T_{prefix} + T_{postfix} \qquad (6)$$

A packet of K OFDM symbols can now be written as:

$$r(t) = \sum_{k=0}^{K} r_k(t - kT_s) \qquad (7)$$

In (6), d_i is the ith QAM value, which is obtained by mapping input bits according to the method described in 1.3.2.4.

$w(t)$ is the raised cosine pulse shaping function with a roll-off factor β of 0.025. It is defined as:

$$w(t) = \begin{cases} 0.5 + 0.5\cos\left(\pi + \dfrac{\tau\pi}{\beta T}\right) & 0 \le \tau \le \beta T \\ 1.0 & \beta T \le \tau \le T_s \\ 0.5 + 0.5\cos\left(\dfrac{(\tau - T_s)\pi}{\beta T}\right) & T_s \le \tau \le T_s + \beta T \end{cases} \qquad (8)$$

The OFDM signal can be generated as follows: first, groups of 48 data symbols d_i are padded with zeros to get blocks of 64 input samples which are used to calculate an Inverse Fast Fourier Transform (IFFT). Then, the last T_{prefix} samples of the IFFT output are inserted at the start of the OFDM symbol, and the first $T_{postfix}$ samples are appended at the end. The OFDM symbol is then multiplied by a raised cosine window $w(t)$ to reduce the power of out-of-band subcarriers. The OFDM symbol is then added to the output of the previous OFDM symbol with a delay of T_s, such that there is an overlap region of βT_s, where β is the roll-off factor the raised cosine window. The time structure of OFDM symbols is depicted in Figure 7. Relevant OFDM parameters are listed in Table 6.

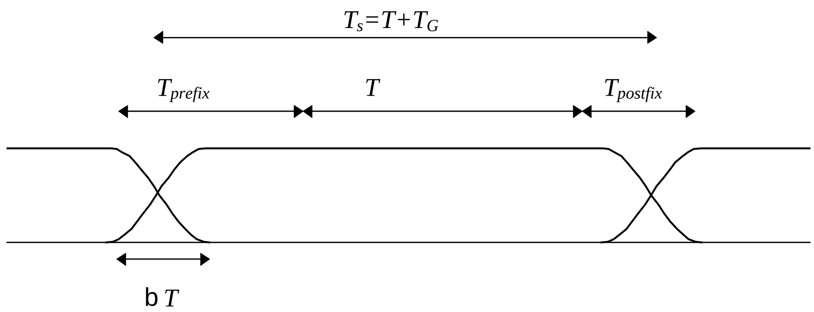

Figure 7: OFDM cyclic extension and windowing.

N_s : Number of subcarriers	48
T_s : Symbol interval	4.8 µs
T : IFFT/FFT period	4.042 µs ($T_s \cdot 64/76$)
T_G : Guard time	758 ns (T_s-T)
T_{prefix} : Pre-guard interval	758 ns (T_s-T)
$T_{postfix}$: Post-guard interval	101 ns (0.025T)
b : Roll-off factor	0.025

Table 6, OFDM parameters

1.3.2.5 Transmit to Receive Turnaround Time

The TX to RX turnaround time shall be less than 5 µs.

The TX to RX turnaround time shall be measured at the air interface from the trailing edge of the last transmitted symbol to valid CCA detection of the incoming signal. The CCA should occur within 10 µs (5 µs for turnaround time plus 5 µs for energy detect) or by the next slot boundary occurring after the 10 µs has elapsed (refer to clause 1.3.4). A receiver input signal 3 dB above the ED threshold described in clause 1.3.4 shall be present at the receiver.

1.3.2.6 Receive to Transmit Turnaround Time

The RX to TX turnaround time shall be measured at the MAC/PHY interface, using PHYTXSTART.request and shall be less than or equal to 5 µs.

1.3.2.7 Slot Time

The slot time for the OFDM PHY shall be the sum of the RX to TX turnaround time (5 µs) and the energy detect time (5 µs specified in clause 1.3.4). The propagation delay shall be regarded to be included in the energy detect time.

1.3.2.8 Transmit and Receive Antenna Port Impedance

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

1.3.2.9 Transmit and Receive Operating Temperature Range

Three temperature ranges for full operation compliance to the OFDM PHY are specified in clause 13. Type 1 shall be defined as 0°C to 40°C is designated for office environments. Type 2 shall be defined as -20°C to +50°C and Type 3 defined as -30°C to +70°C are designated for industrial environments.

1.3.3 PMD Transmit Specifications

The following clauses describe the transmit functions and parameters associated with the Physical Medium Dependent sublayer.

1.3.3.1 Transmit Spectrum Mask

The transmitted spectrum shall have a -20 dBr (dB relative to the spectral density at the carrier frequency) bandwidth not exceeding 20 MHz. The transmitted spectral density of the transmitted signal shall fall within the spectral mask as shown in Figure 8. The measurements shall be made using 100 kHz resolution bandwidth and a 30 kHz video bandwidth.

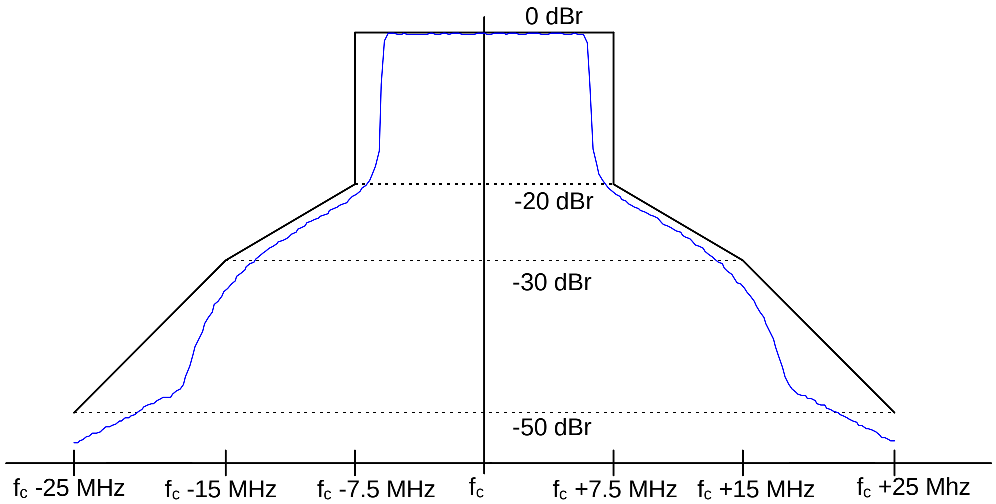

Figure 8, Transmit Spectrum Mask

1.3.3.2 Transmit Center Frequency Tolerance

The transmitted center frequency tolerance shall be +/- 40 ppm maximum.

1.3.3.3 Symbol Clock Frequency Tolerance

The symbol clock frequency tolerance shall be better than +/- 40 ppm maximum.

1.3.3.4 RF Carrier Suppression

The RF carrier suppression shall be at least 15 dB below the peak power spectrum.

1.3.4 Clear Channel Assessment

The OFDM PHY shall provide the capability to perform Clear Channel Assessment (CCA) according to at least one of the following three methods:

CCA Mode 1: Energy above threshold. CCA shall report a busy medium upon detecting any energy above the ED threshold.

CCA Mode 2: Carrier sense only. CCA shall report a busy medium only upon the detection of an OFDM signal. This signal may be above or below the ED threshold.

CCA Mode 3: Carrier sense with energy above threshold. CCA shall report a busy medium upon the detection of an OFDM signal with energy above the ED threshold.

The energy detection status shall be given by the PMD primitive, PMD_ED. The carrier sense status shall be given by PMD_CS. The status of PMD_ED and PMD_CS are used in the PLCP convergence procedure to indicate activity to the MAC through the PHY interface primitive PHY-CCA.indicate.

A Busy channel shall be indicated by PHY-CCA.indicate of class BUSY.

Clear Channel shall be indicated by PHY-CCA.indicate of class IDLE.

The PHY MIB attribute aCCAModeSuprt shall indicate the appropriate operation modes. The PHY shall be configured through the PHY MIB attribute aCurrentCCAMode.

The CCA shall be TRUE if there is no energy detect or carrier sense. The CCA parameters are subject to the following criteria:

a) The energy detection threshold shall be less than or equal to -80 dBm for TX power > 100 mW, -76 dBm for 50 mW < TX power <= 100 mW, and -70 dBm for TX power <= 50 mW.

b) With a valid signal (according to the CCA mode of operation) present at the receiver antenna within 5 µs of the start of a MAC slot boundary, the CCA indicator shall report channel busy before the end of the slot time.

c) In the event that a correct PLCP Header is received, the OFDM PHY shall hold the CCA signal inactive (channel busy) for the full duration as indicated by the PLCP LENGTH field. Should a loss of carrier sense occur in the middle of reception, the CCA shall indicate a busy medium for the intended duration of the transmitted packet.

Conformance to OFDM PHY CCA shall be demonstrated by applying an OFDM compliant signal, above the appropriate ED threshold (a), such that all conditions described in (b) and (c) above are demonstrated.