2 High-rate UWB and 60 GHz communications

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In this chapter, two technologies for high data-rate communications systems for wireless personal area networks (WPANs) are discussed. Namely, the ultrawideband (UWB) technology that operates in the 3.1–10.6 GHz band and the millimeter wave (MMW) technology (also called 60 GHz radio) that can use the 57–64 GHz band in most parts of the world are considered. First, a generic overview is given and various application scenarios are discussed. Then, the ECMA standard for high-rate UWB systems is studied. Finally, two standards for the 60 GHz MMW radio are investigated.

2.1 Overview and application scenarios

In order to realize high-speed communications systems with low power consumption, signals with very large bandwidths need to be employed. One way of designing such communications systems is to use UWB signals as an underlay technology by utilizing all or part of the frequency spectrum between 3.1 and 10.6 GHz [1–3]. According to the US Federal Communications Commission (FCC), a UWB signal is defined as having an absolute bandwidth of at least 500 MHz or a relative (fractional) bandwidth of larger than 20% [3, 4].

In order not to cause any adverse effects on other wireless systems in the same frequency band, such as IEEE 802.11a wireless local area networks (WLANs), certain power emission limits are imposed on UWB devices by regulatory authorities, such as the FCC in the USA [3] and the Electronic Communications Committee (ECC) in Europe [5]. For example, the FCC requires that the average power spectral density (PSD) must not exceed −41.3 dBm/MHz over the frequency band from 3.1 to 10.6 GHz, and it must be even lower outside this band, depending on the specific application [3]. Specifically, Figure 2.1 shows the FCC limits for indoor communications systems.

Due to the regulations on UWB systems, high-rate UWB systems can only be used for short-range applications. Some typical applications can be listed as follows [6, 7]:

wireless peripheral connectivity UWB systems can provide high data rates of the order of several hundreds of megabits per second (Mbps), which can be used to provide high-speed wireless connectivity between PCs and PC peripherals, such as

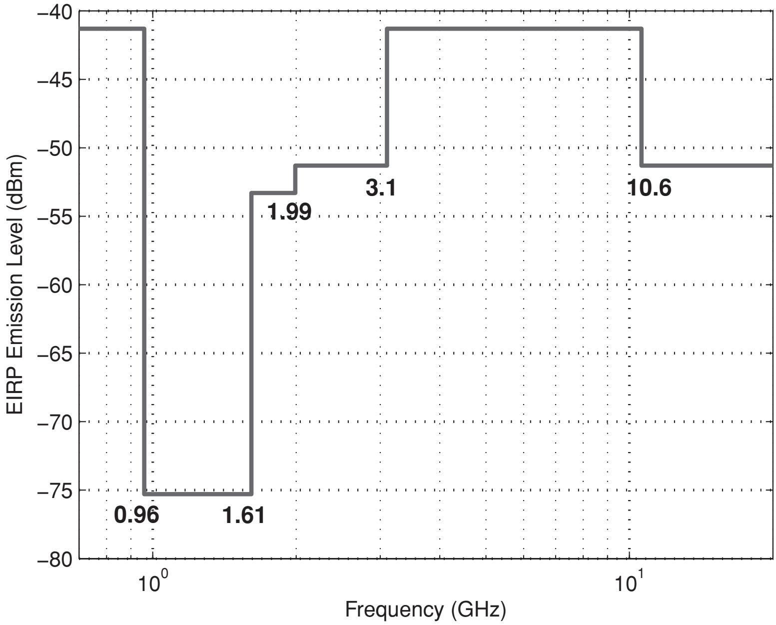

Figure 2.1 FCC emission limits for indoor UWB systems, where EIRP refers to equivalent isotropically radiated power, which is defined as the product of the power supplied to an antenna and its gain in a given direction relative to an isotropic antenna [2].

printers, external storage devices, and scanners. In this context, wireless universal serial bus (USB) is one of the killer applications of high-rate UWB systems [8].

wireless multimedia connectivity UWB systems can provide connectivity for audio and video electronics devices, such as digital cameras, camcorders, MP3 players, and DVDs. However, the current UWB systems, which provide data rates up to 480 Mbps, may not be sufficient for transfer of certain high-definition (HD) video streams.

location based services due to their large bandwidths, UWB signals can be used to obtain accurate position information as well [2]. Therefore, UWB systems can provide location aware services at specific locations.

wireless ad-hoc connections UWB devices can form ad-hoc networks to transfer data between various electronics devices. For example, a digital camera can be connected directly to a printer to print pictures [7].

One of the most important applications of UWB signaling is wireless USB, which is the wireless extension to USB that combines the speed and security of wired technology with the convenience of wireless technology [8]. Wireless USB is based on the multiband orthogonal frequency division multiplexing (MB-OFDM) UWB radio platform, which is discussed in Section 2.2. It provides 480 Mbps at 3 m and 110 Mbps at 10 m. Recently, a number of commercial products have appeared on the market (Figure 2.2).

Another way of designing high-speed systems for short-range wireless communications is to utilize the MMW frequency bands, especially the 60 GHz band [9–13, 19–28].

Figure 2.2 A commercial wireless USB product.

The frequency spectrum from 57 GHz to 64 GHz is allocated for MMW communications in most parts of the world [10–12]. MMW communications systems can provide data rates of a few gigabits per second (Gbps) over ranges up to 10 m [9].

Due to high signal attenuation in the MMW frequency bands, 60 GHz radios transmit significantly more power than other WPAN systems. On the other hand, high attenuation also results in reduced interference levels and efficient frequency reuse. Therefore, very high throughputs can be achieved in a network [11]. Another advantage of using the 60 GHz radio is related to compact component sizes at MMW frequencies, which, for example, facilitates the use of multiple antennas at user terminals [11]. In reference [13], four advantages of 60 GHz communications over UWB communications have been specified as follows:

1. International coordination for the operating spectrum is difficult for UWB, as opposed to 60 GHz communications.
2. UWB systems may suffer from in-band interference from devices such as WLANs at 2.4 GHz and 5 GHz unlicensed bands, while 60 GHz bands are free of major interference sources.
3. While UWB systems can provide data rates up to 480 Mbps, 60 GHz devices are capable of providing data rates on the order of several Gbps.
4. Due to the path loss which depends tightly on the central frequency, the received signal strength may show considerably larger variations over the spectrum of UWB signals (where the spectrum may range between 3.1 GHz and 10.6 GHz), while the dynamic range of path loss over the spectrum range of 60 GHz systems is considerably lower.

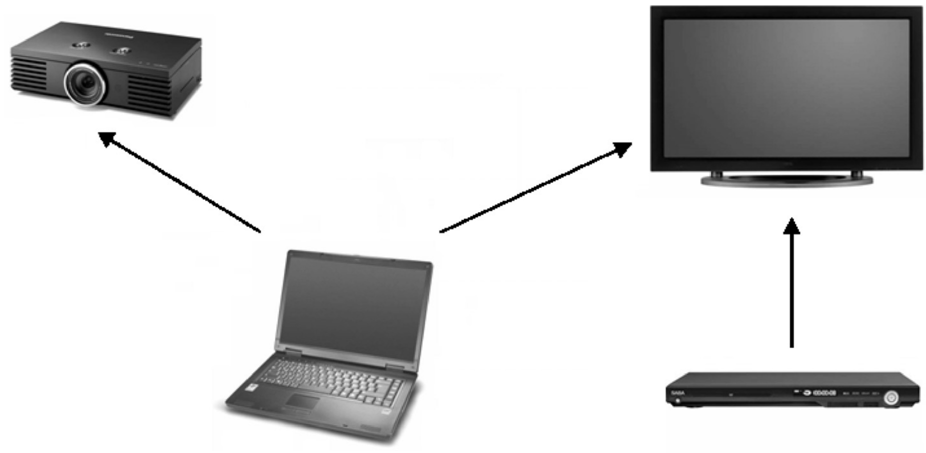

Figure 2.3 Wireless transfer of HD video/audio from a DVD player to an HDTV, and from a laptop to a projector or to an HDTV.

Due to the large bandwidth of 7 GHz allocated to MMW communications systems, various applications that require high-speed data transmission are envisioned. In reference [12], the main application areas are listed as:

- HD video streaming;
- file transfer;
- wireless gigabit Ethernet;
- wireless docking station and desktop point-to-multipoint connections;
- wireless backhaul;
- wireless ad-hoc networks.

One of the most exciting applications of MMW communications is wireless HD video streaming. Currently, high-definition televisions (HDTVs) have various data rates ranging from several hundred Mbps to a few Gbps depending on the resolution and the frame rate. For example, for an HDTV with resolution 1920×1080 and frame rate 60 Hz, the required data rate for wireless HD transmission is around 3 Gbps (considering RGB video format with 8 bits per channel per pixel) [11]. Therefore, multigigabit wireless communications capability of the 60 GHz radio is essential in HD video streaming.

Transfer of HD video/audio streams to an HDTV can come from various devices, such as a laptop, a personal data assistant (PDA), or a portable media player (PMP) [12] (Figure 2.3). In such scenarios, typical communication ranges vary from 3 meters to 10 meters, and both line-of-sight (LOS) and non-line-of-sight (NLOS) connections can be encountered. As another example, HD streams can be sent from a laptop to a projector as shown in Figure 2.3 as well [12].

Another important application of the 60 GHz radio is the wireless transfer of bulky files between various devices [11, 12]. For example, in office or residential environments, wireless file transfer can be performed between a computer and its peripherals such as printers, camcorders, and digital cameras. In addition, it is possible to sell

Table 2.1 Allocation of frequency bands in the ECMA-368 standard.

Band index	Center frequency (GHz)	Band group
1	3.432	1
2	3.960	1
3	4.488	1
4	5.016	2
5	5.544	2
6	6.072	2
7	6.600	3
8	7.128	3
9	7.656	3
10	8.184	4
11	8.712	4
12	9.240	4
13	9.768	5
14	10.296	5

audio/video contents in a kiosk in a store using MMW communications, as mentioned in reference [12].

2.2 ECMA-368 high-rate UWB standard[1]

The main standards for high-rate UWB systems are the *ECMA-368 high-rate UWB PHY and MAC standards* and the *ECMA-369 MAC-PHY interface for ECMA-368* [14, 15].[2] In particular, these ECMA standards specify a basis for high data rate and short-range WPANs, utilizing all or part of the spectrum between 3.1 GHz and 10.6 GHz with data rates of up to 480 Mbps [2].

In the ECMA-368 high-rate UWB standard, the frequency band 3.1–10.6 GHz is divided into 14 bands, with a 528 MHz spacing between consecutive center frequencies. Namely, the center frequency for the nth band, $f_c^{(n)}$, is calculated as

$$f_c^{(n)} = 2.904 + 0.528n \quad \text{(GHz)}, \tag{2.1}$$

for $n = 1, \ldots, 14$. In addition, these 14 frequency bands are classified into 5 band groups as shown in Table 2.1. The transmitted signal at a given time occupies only one of the 14 frequency bands, and time-frequency codes (TFCs) are used to specify the frequency band used by each symbol. For example, Figure 2.4 illustrates a time-frequency plot for six consecutive symbols for a TFC of {1, 2, 3, 1, 2, 3}. In other words, the first, second, and third symbols are transmitted in band 1, band 2, and band 3, respectively; and this structure is repeated for the next three symbols.

[1] This section is adopted from Section 2.3.1 of reference [2].

[2] ECMA International is an industry association that works on the standardization of information and communication technology and consumer electronics (www.ecma-international.org).

Table 2.2 Seven TFCs for band group 1 [2].

TFC-1	1	2	3	1	2	3
TFC-2	1	3	2	1	3	2
TFC-3	1	1	2	2	3	3
TFC-4	1	1	3	3	2	2
TFC-5	1	1	1	1	1	1
TFC-6	2	2	2	2	2	2
TFC-7	3	3	3	3	3	3

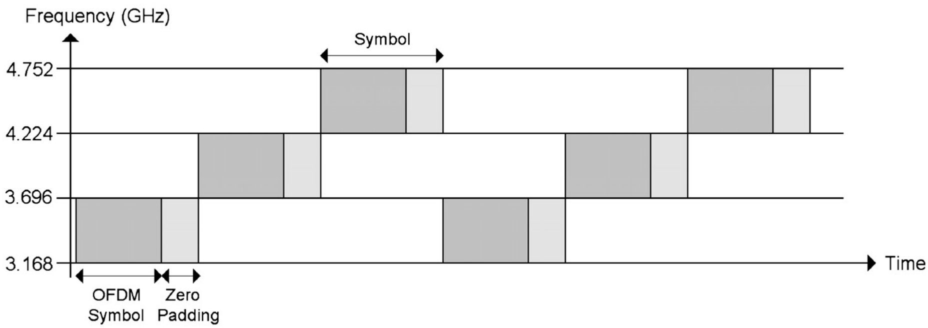

Figure 2.4 Time-frequency plot for a system using the first three bands with a TFC of {1, 2, 3, 1, 2, 3} [2].

The ECMA-368 standard defines a total of seven TFCs for the first band group as shown in Table 2.2. Similarly, seven TFCs are defined for band groups 2, 3, and 4. However, for band group 5, only {13, 13, 13, 13, 13, 13} and {14, 14, 14, 14, 14, 14}, are specified. In this way, a total of 30 channels are specified in the standard. When a TFC consists of at least two distinct band indices, time-frequency interleaving (TFI) is performed as data is interleaved over different bands. Otherwise, data is transmitted over a single band, which is called fixed-frequency interleaving (FFI) [2].

2.2.1 Transmitter structure

The physical layer (PHY) of the ECMA-368 standard is based on MB-OFDM. According to the TFCs described above, OFDM symbols are transmitted in some of the 14 frequency bands. A generic structure of the MB-OFDM transmitter according to the ECMA-368 standard is shown in Figure 2.5. First, information bits to be transmitted are scrambled, and then encoded using a convolutional encoder. A convolutional encoder encodes the input bits by passing them through a linear finite state machine, where the number of states determines the *constraint length* of the code, and the ratio between the number of output bits and the number of input bits specifies the *rate* of the code [2]. In the ECMA-368 standard, a convolutional encoder with rate $1/3$ and constraint length 7 is employed. By using this encoder, various code rates can be obtained via the *puncturing* technique, which omits some of the encoded bits at the output of the encoder to increase the coding rate. For instance, by omitting 7 bits from each 15 encoded output bits of

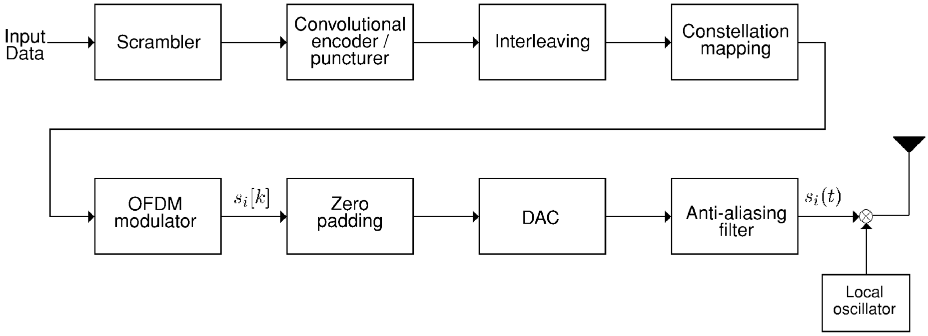

Figure 2.5 Basic blocks of an MB-OFDM UWB transmitter according to the ECMA-368 [2].

the rate 1/3 convolutional encoder, the rate can be increased to 5/8. In the standard, a coding rate of 1/3, 1/2, 5/8, or 3/4 can be used in the system corresponding to various data-rate options [2].

After convolutional encoding, the encoded bits are interleaved, which is a process that spreads bits over a series of symbols in order to provide robustness against burst errors. The ECMA-368 standard defines both inter-symbol and intra-symbol interleaving. For the inter-symbol interleaving, bits are permuted over six symbols, whereas the arrangements of bits inside symbols are changed according to certain structures for the intra-symbol interleaving [2].

After the interleaving operation, the bits are mapped onto a complex constellation. For data rates of 53.3, 80, 106.7, 160, and 200 Mbps, the binary data is mapped to a quadrature phase-shift keying (QPSK) constellation, whereas for data rates of 320, 400, and 480 Mbps, the binary data is mapped to a multidimensional constellation using the dual-carrier modulation (DCM) approach [2]. For QPSK, each pair of binary bits, b_{2i} and b_{2i+1}, is mapped to a complex number given by $\frac{1}{\sqrt{2}}(2b_{2i} - 1 + j(2b_{2i+1} - 1))$ for $i = 0, 1, \ldots$ For DCM, all 200 bits are converted into 100 complex numbers by grouping 200 bits into 50 groups of 4 bits, and then by mapping each 4-bit group onto 2 complex numbers according to a specific pattern, as defined in reference [14].

The complex numbers obtained via constellation mapping are then input to the OFDM modulator in Figure 2.5, and zero padding is applied to the output of the OFDM modulator [2]. Next, the discrete signal is converted into a continuous-time waveform by a digital-to-analog converter (DAC) and an anti-aliasing filter. Finally, depending on the TFC, a local oscillator is employed to set the center frequency of the signal, which is then transmitted through the antenna as shown in Figure 2.5.

2.2.2 Signal model

The mathematical expression for the transmitted packet is given by

$$s_{\text{tx}}(t) = \text{Re}\left\{\sum_{i=0}^{N_s} s_i(t - iT_s)\exp\left(j2\pi f_c^{(q(i))}t\right)\right\}, \tag{2.2}$$

where T_s is the symbol length, N_s is the number of symbols in the packet, $s_i(t)$ is the complex baseband signal representation for the ith symbol, $f_c^{(n)}$ is the center frequency for the nth frequency band, and $q(i)$ is a function that maps the ith symbol to the appropriate frequency band according to the TFC at the transmitter. For example, for the TFC in Figure 2.4, $q(i) = \mathrm{mod}\{i, 3\} + 1$ can be used, where $\mathrm{mod}\{x, y\}$ represents the remainder of the division of x by y [2].

Since each packet consists of a synchronization preamble, a header, and a PHY service data unit (PSDU),[3] the symbol $s_i(t)$ in (2.2) is expressed according to the symbol index as follows:

$$s_i(t) = \begin{cases} s_{\mathrm{sync},i}(t), & 0 \le i < N_{\mathrm{sync}} \\ s_{\mathrm{hdr},i-N_{\mathrm{sync}}}(t), & N_{\mathrm{sync}} \le i < N_{\mathrm{sync}} + N_{\mathrm{hdr}} \\ s_{\mathrm{frame},i-N_{\mathrm{sync}}-N_{\mathrm{hdr}}}(t), & N_{\mathrm{sync}} + N_{\mathrm{hdr}} \le i < N_s \end{cases}, \tag{2.3}$$

where N_{sync} and N_{hdr} are the number of symbols in the synchronization preamble and header sections of the packet, respectively. In the following, the detailed descriptions of the signal structures are provided only for the header and the PSDU. Interested readers are referred to reference [14] for a detailed investigation of the synchronization signals.

Consider the discrete signal $s_i[k]$, which is obtained by taking the IDFT of the complex modulated data:

$$s_i[k] = \frac{1}{\sqrt{N_{\mathrm{FFT}}}} \sum_{l=-61}^{61} b_{i,l} \exp\left(j2\pi lk/N_{\mathrm{FFT}}\right), \tag{2.4}$$

for $i = N_{\mathrm{sync}}, \ldots, N_s - 1$ and $k = 0, 1, \ldots, N_{\mathrm{FFT}} - 1$, where $b_{i,l}$ is the complex information at the lth subcarrier of the ith symbol, and N_{FFT} is the size of the IDFT. Note that $s_i[k]$ in (2.4) is an OFDM symbol, which effectively divides the frequency spectrum of 528 MHz into overlapping but orthogonal subbands by using N_{FFT} subcarriers and transmits information symbols ($b_{i,l}$) at each subcarrier [2, 16].

The ECMA-368 standard specifies that the total number of subcarriers N_{FFT} is 128, and out of 128 subcarriers 122 are used in the system, as can be noted from (2.4) (the subcarrier corresponding to the DC component is set to zero; i.e., $b_{i,0} = 0$). The subcarriers are classified as data subcarriers, pilot subcarriers, and guard subcarriers. According to the standard, there are 100 data subcarriers that are used to carry information, whereas there exist 12 pilot subcarriers that transmit known data for the purpose of signal parameter estimation at the receiver. Also, there are 10 guard subcarriers, 5 on each side of the OFDM symbol, that carry the same information as the outermost data subcarriers [2, 14].

In order to mitigate the effects of multipath propagation and to provide a time window to allow the transmitter and the receiver sufficient time to switch between the different bands, zero-padding is applied to $s_i[k]$ after the IDFT operation, and $s_{\mathrm{frame},i}[k]$ and

[3] The PSDU is formed by concatenating the frame payload with the frame check sequence, tail bits, and pad bits, which are inserted in order to align the data stream on the boundary of the symbol interleaver [14].

Table 2.3 Various data rate options and corresponding parameters in the ECMA-368 standard [2].

Data rate (Mbps)	Modulation	Coding rate	FDS factor	TDS factor
53.3	QPSK	1/3	2	2
80	QPSK	1/2	2	2
106.7	QPSK	1/3	1	2
160	QPSK	1/2	1	2
200	QPSK	5/8	1	2
320	DCM	1/2	1	1
400	DCM	5/8	1	1
480	DCM	3/4	1	1

$s_{\mathrm{hdr},i}[k]$ are obtained as

$$s_{\mathrm{hdr},i}[k] = \begin{cases} s_i[k], & k = 0, 1, \ldots, N_{\mathrm{FFT}} - 1, \\ 0, & k = N_{\mathrm{FFT}}, \ldots, N_{\mathrm{s}} - 1, \end{cases} \quad (2.5)$$

for $i = N_{\mathrm{sync}}, \ldots, N_{\mathrm{sync}} + N_{\mathrm{hdr}} - 1$, and

$$s_{\mathrm{frame},i}[k] = \begin{cases} s_i[k], & k = 0, 1, \ldots, N_{\mathrm{FFT}} - 1, \\ 0, & k = N_{\mathrm{FFT}}, \ldots, N_{\mathrm{s}} - 1, \end{cases} \quad (2.6)$$

for $i = N_{\mathrm{sync}} + N_{\mathrm{hdr}}, \ldots, N_{\mathrm{s}} - 1$. Then, from the discrete-time signals $s_{\mathrm{hdr},i}[k]$ and $s_{\mathrm{frame},i}[k]$, the continuous-time symbols $s_i(t)$ are obtained by digital-to-analog conversion and filtering, as shown in Figure 2.5.

2.2.3 System parameters

Table 2.3 lists the data rates supported by the ECMA-368 standard that range from 53.3 Mbps to 480 Mbps. Note that various data rates are achieved by adjusting the rate of convolutional encoder, and/or by using spreading in the time and/or frequency domain. In the time-domain spreading (TDS), the same information is transmitted across two consecutive OFDM symbols, whereas in the frequency-domain spreading (FDS) the same information is transmitted on two separate subcarriers within an OFDM symbol [2].

In Table 2.4, the main system parameters are listed. As each symbol is transmitted over 312.5 ns and 100 data subcarriers are transmitted per symbol, a total of 3.2×10^8 subcarriers are transmitted per second. Since each subcarrier carries two bits of information (for both QPSK and DCM), the raw data rate is obtained as 640 Mbps. Then, according to the rate R of the convolutional encoder, and the TDS and FDS factors, the data rate can be calculated as

$$\text{Data rate} = \frac{\text{Raw data rate} \times R}{N_{\mathrm{TDS}} \times N_{\mathrm{FDS}}}\,, \quad (2.7)$$

where N_{TDS} and N_{FDS} denote the TDS and FDS factors, respectively. Note that the data rates listed in Table 2.3 can be obtained from the relation in (2.7). For example, the

Table 2.4 Systems parameters for the MB-OFDM UWB transmitter according to the ECMA-368 standard [2].

Parameter	Definition	Value
N_{FFT}	Total number of subcarriers (FFT size)	128
N_T	Total number of subcarriers used	122
N_D	Number of data subcarriers	100
N_P	Number of pilot subcarriers	12
N_G	Number of guard subcarriers	10
T_s	Symbol interval	312.5 ns
T_{FFT}	IFFT and FFT period	242.42 ns
T_{ZP}	Zero-padding duration	70.08 ns
T_{switch}	Time to switch between bands	9.47 ns

highest data rate of 480 Mbps is achieved for $R = 3/4$, $N_{TDS} = 1$, and $N_{FDS} = 1$; that is, 640 Mbps $\times (3/4)/(1 \times 1) = 480$ Mbps.

2.3 ECMA-387 millimeter-wave radio standard

The main standards for millimeter wave communications are as follows:

- ECMA-387 high rate 60 GHz PHY, MAC, and HDMI PAL standard [17];
- IEEE 802.15.3c wireless MAC and PHY standard for high rate WPANs [18].

While there are several similarities between the two standards, they also have their own unique features. For example, ECMA-387 uses a distributed MAC protocol based on specifications by WiMedia, while IEEE 802.15.3c uses a centralized MAC architecture [19]. In this section, important features of the ECMA-387 standard will be reviewed in detail, and the next section will summarize some unique features of the IEEE 802.15.3c standard. While IEEE 802.11 TGad is also working on a millimeter wave standard with a target completion date of December 2012, it will not be specifically discussed in this chapter.

ECMA International TC48 completed its millimeter wave standard ECMA-387 in December 2008. The main applications targeted by the standard are bulk data transfer and high-definition video streaming at very high data rates. In ECMA 387, the frequency range between 57 GHz and 66 GHz is divided into four channels each having an equal bandwidth of 2.16 GHz. There exists a 240 MHz of guardband between 57 and 57.24 GHz, while another guardband of 120 MHz is placed between 65.88 and 66 GHz. Table 2.5 summarizes the unique band numbering system specified in ECMA-387 for the utilization of all four channels as well as their different combinations, where f_L, f_C, and f_U, denote the lower frequency, central frequency, and upper frequency for each band, respectively.

Three types of device are defined in the ECMA-387 standard depending on their capabilities: Type A devices, Type B devices, and Type C devices [17, 20]. While all of

Table 2.5 Band allocation in ECMA 387 [17].

Band ID	Channel bonding	f_L (GHz)	f_C (GHz)	f_U (GHz)
1	No	57.24	58.32	59.40
2	No	59.40	60.48	61.56
3	No	61.56	62.64	63.72
4	No	63.72	64.80	65.88
5	1 and 2	57.24	59.40	61.56
6	2 and 3	59.40	61.56	63.72
7	3 and 4	61.56	63.72	65.88
8	1, 2, and 3	57.24	60.48	63.72
9	2, 3, and 4	59.40	62.64	65.88
10	1, 2, 3, and 4	57.24	61.56	65.88

Table 2.6 Device types in ECMA-387 and corresponding data rates [17].

Device type	Mode	Transmission scheme	Data rate
Type A	Mandatory	SCBT (A0)	0.397 Gbps
	Optional	SCBT	0.794 to 6.350 Gbps (no CB)
	Optional	OFDM	1.008 to 4.032 Gbps
Type B	Mandatory	DBPSK	0.794 to 1.588 Gbps (no CB)
	Optional	DQPSK, UEP-QPSK, Dual-AMI	3.175 Gbps
Type C	Mandatory	OOK	0.8 Gbps and 1.6 Gbps
	Optional	4ASK	3.2 Gbps

the four bands in Table 2.5 may be used individually, Type A and Type B devices may also use channel bonding (CB) to combine multiple of these bands in order to achieve higher data rates. All three devices can operate independently; moreover, they can also coexist and inter-operate with each other. Some of the important characteristics of these three different device types are summarized in Table 2.6, which will be further discussed below.

Type A devices can be considered as high-end devices which may typically be used for video/data services over LOS/NLOS links with trainable antennas. They have significant baseband DSP capabilities, which enable the implementation of sophisticated equalization and FEC techniques. Type A devices have two main transmission schemes: single carrier block transmission (SCBT) and orthogonal frequency division multiplexing (OFDM). The cyclic prefix (CP) size may be selected among four different options for SCBT (0, 32, 64, or 96 symbols), while a fixed CP size of 64 symbols is considered for OFDM. Having a variable CP size in SCBT allows good performance in varying multipath environments. As specified in Table 2.6, using Type A devices with SCBT and no CB, ECMA-387 is capable of achieving data rates up to 6.35 Gbps. On the other hand, SCBT with channel bonding is capable of achieving data rates as large as 25.402 Gbps when all the available bands are utilized (see Section 10.2.1 in reference [17]).

Table 2.7 Transmit spectral mask requirements in ECMA-387 for Type A, Type B, and Type C devices (in MHz) [17].

Device type	Channel bonding	f_0	f_1	f_2	f_3	f_4
A and B	Single channel	N/A	1050	1080	1500	2000
C	Single channel	4	1050	1080	1500	2000
A and B	Two bonded channels	N/A	2100	2160	3000	4000
A and B	Three bonded channels	N/A	3150	3240	4500	6000
A and B	Four bonded channels	N/A	4200	4320	6000	8000

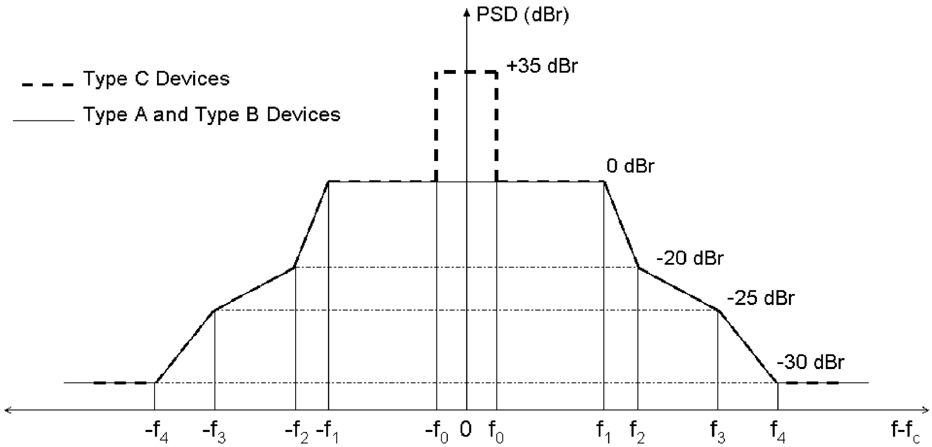

Figure 2.6 Transmit spectrum mask for Type A, Type B, and Type C devices in ECMA-387 [17].

Type B devices specified in ECMA-387 use a simplified single-carrier transmission scheme. They can be considered as economy devices that may be used for video and data services over LOS links with non-trainable antennas. Cyclic prefix is not supported by Type B devices, and there is no discovery mode for antenna training. In the mandatory mode, differential BPSK (DBPSK) is utilized, which is capable of achieving data rates on the order of 0.8 Gbps. On the other hand, up to 3.2 Gbps data rates can be achieved with the optional mode.

Finally, Type C devices are the bottom-end devices with an extremely short range of operation (less than 1 m), inexpensive PHY implementation, and nontrainable antennas. Both coherent and noncoherent detection is possible with Type C devices, thanks to the use of amplitude shift keying (ASK) modulation. As opposed to Type A and Type B devices, channel bonding is not supported for Type C devices.

The PSD masks for Type A, Type B, and Type C devices are shown in Figure 2.6, where the parameters, f_0, f_1, f_2, f_3, and f_4 are specified in Table 2.7. Note that since channel bonding is not possible for Type C devices, the spectral mask applies only to single channel transmissions. On the other hand, spectral masks for Type A and Type B devices are applicable to single channel transmission, as well as channel bonding with two, three, or four bonded channels. Since Type C devices generate a single line spectrum

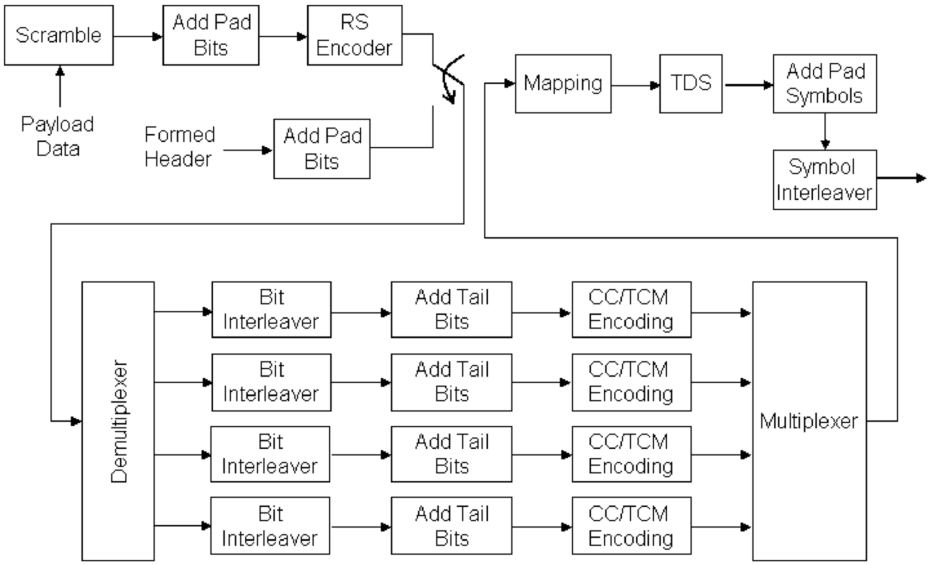

Figure 2.7 Block diagram of the SCBT PHY baseband of Type A devices in ECMA-387 (with EEP) [17].

at the center frequency f_c, the PSD mask for Type C devices allows an extra 35 dBr transmission power over the PSD of Type A and Type B devices in the frequency range from −4 MHz to 4 MHz.[4]

2.3.1 Transmitter structure

As discussed, both single-carrier and OFDM-based transmissions are possible in the ECMA-387 standard. In this section, the transmitter structures for Type A (both for SCBT and OFDM), Type B, and Type C devices will be reviewed based on the specifications in reference [17].

2.3.1.1 Type A devices

A general view of the encoding procedure for Type A SCBT with equal error protection (EEP) is illustrated in Figure 2.7. First, the payload data to be transmitted is scrambled, followed by inclusion of pad bits. Then, a systematic Reed–Solomon (RS) encoder RS(255, 239) defined over Galois field GF(2^8) and having primitive polynomial $p(z) = z^8 + z^4 + z^2 + 1$ is used to encode the output bit stream from the output of bit padding. The RS encoded bits are then demultiplexed to obtain four bit streams, and each bit stream is interleaved by a bit interleaver of length 48. After the inclusion of tail bits, each bit stream goes through a convolutional encoder using an appropriate coding rate of $R = 4/7, 2/3, 4/5, 5/6, 6/7$. In particular for non-square 8QAM (NS8QAM) and 16QAM modulation schemes, trellis coded modulation (TCM) is utilized. Then, the

[4] dBr denotes the relative power difference in decibels.

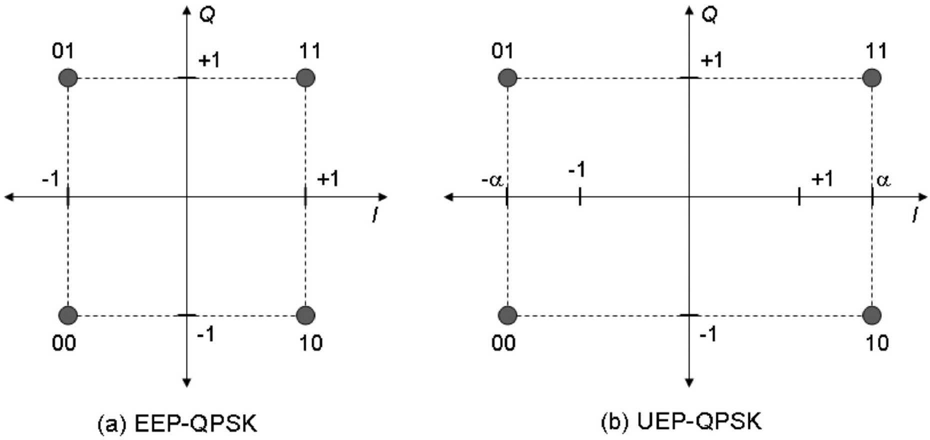

Figure 2.8 Constellation of QPSK modulation with (a) EEP, and (b) UEP.

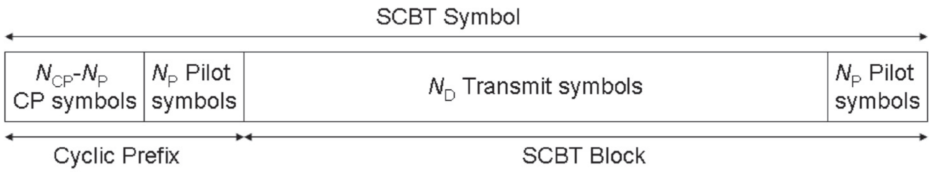

Figure 2.9 An example of the SCBT symbol structure.

coded bits from the four streams are multiplexed to obtain a single stream, which is mapped to the constellations based on the targeted data rate. Obtained data symbols are repeated consecutively by N_{TDS} times at the TDS stage, and fed into a symbol interleaver after inclusion of pad symbols. The symbol interleaver uses a 21 by 24 dual helical scan interleaver to obtain output symbols to be transmitted, where the data symbols are written and read in a memory block with a helical scan pattern [17].

For the case of SCBT with unequal error protection (UEP), the transmitter structure is similar to the one in Figure 2.7, with the exception of splitting least significant bits (LSBs) and most significant bits (MSBs) before scrambling the payload data. This ensures that the bits that require higher reliability are more robust to demodulation errors at the receiver. For example, the MSBs of the color pixel have more significant impact on the video quality compared to the LSBs, and require higher reliability. Example constellations for QPSK modulation with EEP and UEP are illustrated in Figure 2.8(a) and Figure 2.8(b), respectively. While the constellation points are uniformly spaced for EEP-QPSK modulation, the Euclidean distance between the constellation points with different MSB bits is scaled by α for the UEP-QPSK modulation. In ECMA-387 [17], α is taken as 1.25.

After the multiplexed transmit symbols are obtained, the SCBT symbol is generated as shown in Figure 2.9. The transmit data symbols are divided into blocks of length $N_D = 252$, each of which is appended with a pilot symbol sequence of length $N_P = 4$ to obtain the SCBT block. The SCBT block is then prefixed with a cyclic prefix of length

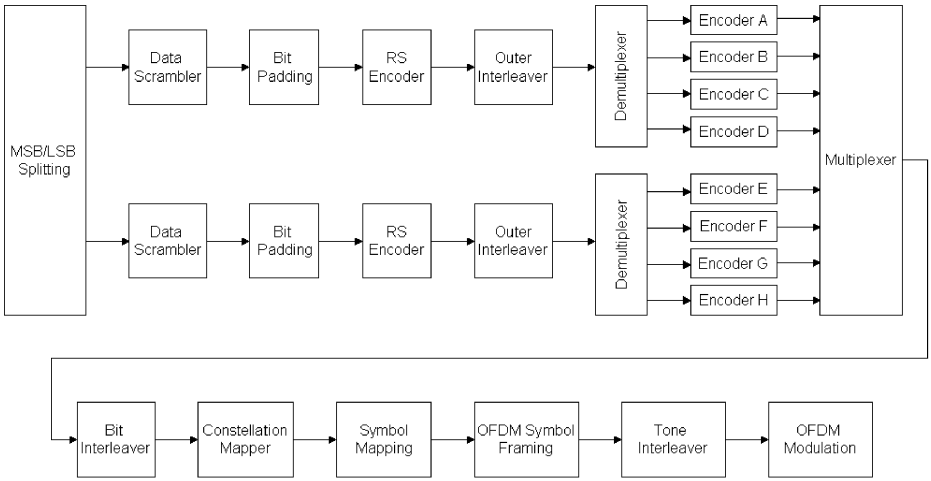

Figure 2.10 Block diagram of the OFDM PHY baseband of Type A devices in ECMA-387 [17].

$N_{CP} \in \{0, 32, 64, 96\}$ symbols that is composed of the last N_{CP} symbols of the SCBT symbol.

Apart from SCBT, OFDM transmission is also specified in ECMA-387 and is summarized in the block diagram in Figure 2.10. For the UEP case, the information bits are split into two streams, and they are passed through data scrambler, bit padding, and RS encoder, respectively, as discussed for the case of SCBT. This is followed by an additional outer interleaver step for OFDM PHY before demultiplexing of the bits. The demultiplexing stages yield four bit streams for the MSBs and another four bit streams for the LSBs, which are then processed by eight parallel convolutional encoders, labeled A–H, as shown in Figure 2.10. Each of the eight parallel convolutional encoders uses a constraint length $K = 7$, a mother code rate of $1/3$, delay memory of 6, and a generator polynomial $g_0 = 133_O$, $g_1 = 171_O$, and $g_2 = 165_O$ and $g_2 = 165_O$, where subscript O denotes octet representation.[5] This is followed by a puncturing stage where the puncturing yields one of the code rates $4/7$, $2/3$, or $4/5$. The multiplexing and bit-interleaving stages combine and interleave the eight different bit streams, and a mapping stage maps the bits onto the symbol constellations based on the desired data rate and the UEP/EEP specification. After symbol padding where the resulting data symbols are appended with $N_{\text{padsym,OFDM}}$ zero symbols, the symbols are mapped to the subcarriers through OFDM PHY modulation. The subcarriers are numbered from -256 to 255, where the null subcarriers are given by the subcarriers within the range $[-256, \ldots, -190]$ and $[190, \ldots, 255]$, the pilot subcarriers are given by the subcarriers $\pm[14, 39, 64, 89, 114, 139, 164, 189]$, and the DC subcarriers are given by the subcarriers $[-1, 0, 1]$. All the remaining subcarriers are used for carrying data. The generated complex symbols are sequentially mapped to data subcarriers. In order to guarantee that neighboring data

[5] For example, 165_O is 001110101 in its binary form and it corresponds to generating polynomial $g_2 = X^6 + X^5 + X^4 + X^2 + 1$.

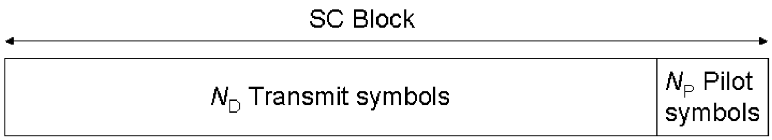

Figure 2.11 An example for SC symbol structure.

symbols are mapped onto separate subcarriers, all of the modulated QPSK and QAM symbols are also interleaved by a block interleaver that has a block size equivalent to the size of FFT in a single OFDM symbol.

Before reviewing the transmitter structure of Type B and Type C devices in ECMA-387, it is worth comparing some tradeoffs between single-carrier transmission and multi-carrier transmission for 60 GHz communications. In reference [13], it was discussed that NLOS multipath components may be subject to larger path loss compared to LOS multipath components for higher central frequencies. Moreover, directional antennas and beamforming techniques are popularly used for 60 GHz communications owing to the advantages of antenna design at higher central frequencies. These facts imply that the mitigation of multipath propagation effects for millimeter wave wireless systems may have less importance than wireless systems at lower central frequencies. Therefore, the single-carrier approach becomes a competitive low-end transmission scheme compared to the OFDM-based transmission for 60 GHz communication systems. As illustrated in Table 2.6, using single-carrier transmission along with a low-complexity modulation scheme such as on-off keying (OOK), data rates of the order of 1.6 Gbps can be achieved. On the other hand, OFDM still offers a viable alternative for NLOS environments, where frequency domain equalization may be easily implemented.

2.3.1.2 Type B devices

The transmitter structure for Type B devices with EEP is similar to the SCBT transmitter structure in Figure 2.7, with the difference that Type B devices do not have tail bit inclusion and CC/TCM encoding stages. Moreover, after the symbol interleaver, a differential encoder is included in Type B devices. For modes B0, B1, and B2 specified in Table 2.10, the padded data symbols $v[n]$ should be differentially encoded to obtain encoded data symbols $t[n]$ as follows

$$t[n] = \begin{cases} v[n] & \text{if } n \bmod N_{\mathrm{D}} = 0 \\ t[n-1]v[n]/\left|v[n-1]\right| & \text{if } n \bmod N_{\mathrm{D}} > 0\,. \end{cases} \tag{2.8}$$

In the case of UEP, the payload data is split into MSB and LSB prior to the scrambling stage. After RS encoding, demultiplexing, bit interleaving (eight streams), and multiplexing stages, the bits are mapped into constellation diagrams using one of the DBPSK, DQPSK, or UEP-QPSK modulations specified later in Table 2.10. Once the transmit symbols are obtained, they are transmitted using the SC block illustrated in Figure 2.11. Each of the N_{D} transmit symbols is appended with $N_{\mathrm{P}} = 4$ pilot symbols prior to transmission.

Type B devices in ECMA-387 also support a dual alternate mark inversion (DAMI) mode (see Table 2.10), which uses a single sideband (SSB) modulated signal

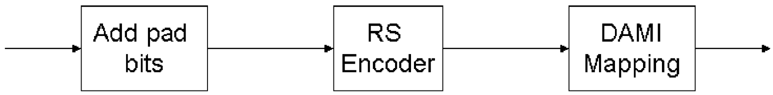

Figure 2.12 Encoding and mapping for DAMI devices [17].

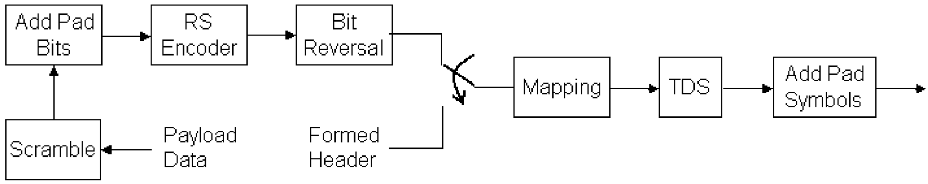

Figure 2.13 Encoding procedure for Type C devices in ECMA-387 [17].

accompanied with two pilot tones. It is a low-complexity transmission method as illustrated in Figure 2.12. After the RS encoder, the coded binary serial input data $b[k]$ is used to obtain an intermediate binary stream $\hat{b}[k]$ as follows: $\hat{b}[k] = \hat{b}[k-2] \oplus b[k]$, where modulo-2 addition is indicated by $\oplus$, and $\hat{b}[-2] = \hat{b}[-1] = 0$. The output of the DAMI encoder is given by

$$d[k] = \sqrt{2}\, I[k]\,, \tag{2.9}$$

where

$$I[k] = \begin{cases} 0\,, & \text{if } \hat{b}[k-2] = 0\,,\ \hat{b}[k] = 0 \\ 1\,, & \text{if } \hat{b}[k-2] = 0\,,\ \hat{b}[k] = 1 \\ -1\,, & \text{if } \hat{b}[k-2] = 1\,,\ \hat{b}[k] = 0 \\ 0\,, & \text{if } \hat{b}[k-2] = 1\,,\ \hat{b}[k] = 1 \end{cases}. \tag{2.10}$$

2.3.1.3 Type C devices

The transmitter structure for the Type C devices in ECMA-387 is illustrated in Figure 2.13, which is a considerably simpler structure than SCBT in Figure 2.7. Prior to mapping the coded bits on the constellation diagrams, an additional stage that does not exist in Type A and Type B devices is the bit reversal stage, where, given the input bit sequence $b[n]$, the output bit sequence is given by $g[n] = \text{NOT}(b[n])$, with NOT(.) denoting the bitwise NOT operation. For the constellation mapping, either the OOK or the 4ASK modulations is used. The SC block is generated as shown in Figure 2.11, where $N_D = 508N_{TDS}$ data symbols and $N_P = 4N_{TDS}$ pilot symbols form one SC block.

2.3.2 Signal models

The radio frequency signal for the transmission schemes of SCBT, OFDM, DBPSK, DQPSK, UEP-QPSK, OOK, and 4ASK specified in Table 2.6 can be expressed in a unified way as follows [17]

$$s_{\mathrm{RF}}(t) = \mathrm{Re}\left\{ \sum_{n=0}^{N_\mathrm{f}-1} s_n\left(t - nT_{\mathrm{sym}}\right) \exp(j2\pi f_\mathrm{c} t) \right\}, \tag{2.11}$$

where Re{.} captures the real part of a signal, T_{sym} is the symbol duration, N_f is the number of symbols in a frame, f_c is the center frequency, and $s_n(t)$ is the complex baseband signal for the nth symbol. The general format for the PHY layer protocol data unit (PPDU) may be composed of four major components: preamble, header, payload, and antenna training sequence (ATS). Hence, $s_n(t)$ can be written in different forms as follows depending on its location within the frame:

$$s_n(t) = \begin{cases} s_{\mathrm{prm},n}(t)\,, & 0 \le n < N_{\mathrm{prm}} \\ s_{\mathrm{hdr},n-N_{\mathrm{prm}}}(t)\,, & N_{\mathrm{prm}} \le n \le N_{\mathrm{prm}} + N_{\mathrm{hdr}} \\ s_{\mathrm{pyl},n-N_{\mathrm{prm}}-N_{\mathrm{hdr}}}(t)\,, & N_{\mathrm{prm}} + N_{\mathrm{hdr}} \le n \le N_{\mathrm{prm}} + N_{\mathrm{hdr}} + N_{\mathrm{pyl}} \\ s_{\mathrm{ATS},n-N_{\mathrm{prm}}-N_{\mathrm{hdr}}-N_{\mathrm{pyl}}}(t)\,, & N_{\mathrm{prm}} + N_{\mathrm{hdr}} + N_{\mathrm{pyl}} \le n \le N_{\mathrm{prm}} + N_{\mathrm{hdr}} \\ & \quad + N_{\mathrm{pyl}} + N_{\mathrm{ATS}} \end{cases}, \tag{2.12}$$

where $s_{\mathrm{prm},n}(t)$, $s_{\mathrm{hdr},n}(t)$, $s_{\mathrm{pyl},n}(t)$, and $s_{\mathrm{ATS},n}(t)$ are the nth symbols of the preamble, header, payload, and ATS, respectively, while N_{prm}, N_{hdr}, N_{pyl}, and N_{ATS} denote the number of symbols in the preamble, header, payload, and ATS, respectively. The total number of symbols within a frame is given by $N_\mathrm{f} = N_{\mathrm{prm}} + N_{\mathrm{hdr}} + N_{\mathrm{pyl}} + N_{\mathrm{ATS}}$. Note that $s_n(t)$ is created by passing the real and imaginary components of the discrete-time signal $s_n[k]$ through DACs and using reconstruction filters after DACs. Details on the generation of $s_n[k]$ are discussed for different device types in Section 2.3.1.

The ECMA-387 standard also includes a discovery mode that is used for communications before the training of antenna arrays. During the discovery mode, ECMA-387 uses a concatenation of a wideband preamble and a narrowband preamble as shown in Figure 2.14. While the signal model for the wideband preamble complies with (2.12), the narrowband preamble shall be modulated using three carriers at frequencies f_c, $f_\mathrm{c} + f_0$, and $f_\mathrm{c} - f_0$, where the transmitted RF signal can be written as [17]

$$s_{\mathrm{RF}}(t) = \mathrm{Re}\left\{ \sum_{n=0}^{N_{\mathrm{NB}}-1} s_{\mathrm{NB},n}(t - nT_{\mathrm{sym}})\Big[\exp(j2\pi f_\mathrm{c} t) + \exp\left(j2\pi [f_\mathrm{c} - f_0]t\right) + \exp\left(j2\pi [f_\mathrm{c} + f_0]t\right)\Big] \right\}, \tag{2.13}$$

where $N_{\mathrm{NB}} = 163\,839$ is the number of symbols in the narrowband preamble, $f_0 =$ 720 MHz is the offset frequency, and $s_{\mathrm{NB},n}(t)$ denotes the nth symbol of the narrowband preamble.

The narrowband preamble is obtained through the concatenation of four copies of a preamble sequence $P_0[.]$, appended by a copy of the same preamble sequence multiplied by -1. The wideband preamble is composed of the concatenation of six copies of a preamble sequence $P_1[.]$, followed by a sequence $P_{1\mathrm{h}}[.]$, and three copies of sequence

Table 2.8 Discovery modes with different data rates [17].

Mode	$N_{DISCREP}$	Data rate (Mbps)
D0	128	2.255
D1	64	4.510
D2	32	9.020
D3	16	18.041
D4	8	36.082
D5	4	72.164
D6	2	144.327
D7	1	288.655

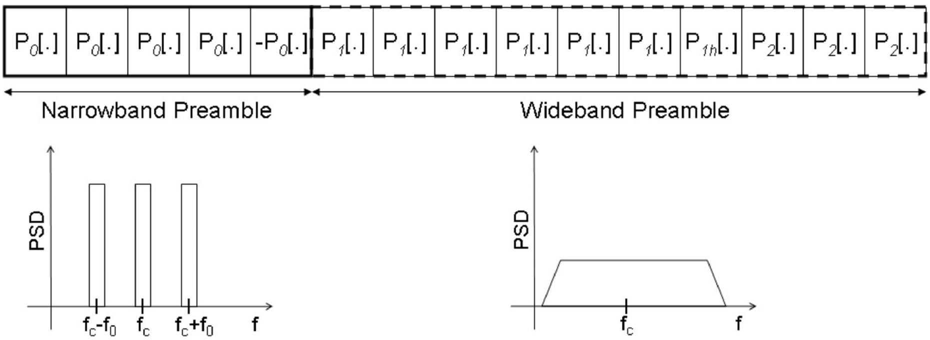

Figure 2.14 Discovery mode preamble structure in ECMA-387 [17].

$P_2[.]$. Since there is no array gain prior to training, the discovery mode increases the SINR through repetition. As shown in Table 2.8, eight different modes (D0-D7) are specified in the standard with different repetition factors N_{DISCREP}, and the data rate for the discovery mode may vary between 2.255 Mbps and 288.655 Mbps. Among 10 different channels specified in Table 2.5, the channel with the BAND_ID = 3 shall be used specifically as the discovery channel.

Finally, Type B devices in ECMA-387 support a dual alternate mark inversion (DAMI) mode (see Table 2.10), which uses a single sideband (SSB) modulated signal accompanied by two pilot tones. The SSB signal can be written as [17]

$$s_{\mathrm{SSB}}(t) = s(t)\cos(2\pi f_{\mathrm{c}} t) + \hat{s}(t)\sin(2\pi f_{\mathrm{c}} t)\,, \tag{2.14}$$

where $\hat{s}(t)$ is the Hilbert transform of $s(t)$, and the baseband signal $s(t)$ can be represented by

$$s(t) = \sum_{k=0}^{N_{\mathrm{f}}-1} d[k]g(t - kT_{\mathrm{sym}})\,, \tag{2.15}$$

where $d[k] \in \{-1, 0, 1\}$ is the kth symbol of the modulated data and $g(t)$ is the baseband pulse shape. How $d[k]$ is generated in preamble, header, and payload is specified further in reference [17].

Table 2.9 Mode dependent parameters for Type A devices [17].

	Base data rate (Gbps)									
Mode	$N_B = 1$	$N_B = 2$	$N_B = 3$	$N_B = 4$	Mod.	Const.	Encoding	R_{CC}	N_{TDS}	N_{tl}
A0	0.397	0.794	1.191	1.588	SCBT	BPSK	RS & CC	1/2	2	4
A1	0.794	1.588	2.381	3.175	SCBT	BPSK	RS & CC	1/2	1	4
A2	1.588	3.175	4.763	6.350	SCBT	BPSK	RS	1	1	0
A3	1.588	3.175	4.763	6.350	SCBT	QPSK	RS & CC	1/2	1	4
A4	2.722	5.443	8.165	10.88	SCBT	QPSK	RS & CC	6/7	1	6
A5	3.175	6.350	9.526	12.70	SCBT	QPSK	RS	1	1	0
A6	4.234	8.467	13.70	16.94	SCBT	NS8QAM	RS & TCM	5/6	1	8
A7	4.763	9.526	14.29	19.05	SCBT	NS8QAM	RS	1	1	0
A8	4.763	9.526	14.29	19.05	SCBT	TCM-16QAM	RS & TCM	2/3	1	6
A9	6.350	12.70	19.05	**25.40**	SCBT	16QAM	RS	1	1	0
A10	1.588	3.175	4.763	6.350	SCBT	QPSK	RS & UEP-CC	R_{MSB}:1/2	1	4
A11	4.234	8.467	12.70	16.93	SCBT	16QAM	RS & UEP-CC	R_{MSB}:4/7 R_{LSB}:4/5	1	4
A12	2.117	4.234	6.350	8.467	SCBT	UEP-QPSK	RS & CC	2/3	1	4
A13	4.234	8.467	12.70	16.93	SCBT	UEP-16QAM	RS & CC	2/3	1	4
A14	1.008	N/A	N/A	N/A	OFDM	QPSK	RS & CC	1/3	1	6
A15	2.016	N/A	N/A	N/A	OFDM	QPSK	RS & CC	2/3	1	6
A16	4.032	N/A	N/A	N/A	OFDM	16QAM	RS & CC	2/3	1	6
A17	2.016	N/A	N/A	N/A	OFDM	QPSK	RS & UEP-CC	R_{MSB}:4/7 R_{LSB}:4/5	1	6
A18	4.032	N/A	N/A	N/A	OFDM	16QAM	RS & UEP-CC	R_{MSB}:4/7 R_{LSB}:4/5	1	6
A19	2.016	N/A	N/A	N/A	OFDM	UEP-QPSK	RS & CC	2/3	1	6
A20	4.032	N/A	N/A	N/A	OFDM	UEP-16QAM	RS & CC	2/3	1	6
A21	2.016	N/A	N/A	N/A	OFDM	QPSK	RS & CC	R_{MSB}:2/3	1	6

2.3.3 System parameters

In this section, mode-dependent, time-dependent, and frame-dependent system parameters for different device types in the ECMA-387 standard are summarized.

2.3.3.1 Mode-dependent parameters

ECMA-387 devices may have different peak data rates based on the number of bonded channels, choice for single-carrier or multicarrier transmission, constellation scheme, encoding mechanism, time-domain spreading, and number of tail bits employed. Depending on different combinations of all these different parameters, 22 different operation modes are defined for Type A devices (A0–A21), 5 different operation modes are defined for Type B devices (B0–B4), and 3 different operation modes are defined for Type C devices (C0–C2).

Mode-dependent parameters for Type A devices and corresponding data rates for different channel-bonding approaches are summarized in Table 2.9. The base data rates assume a cyclic prefix length of zero, N_B denotes the number of bonded channels, R_{CC} denotes the CC code rate, N_{TDS} denotes the time domain spreading factor, and N_{tl}

Table 2.10 Mode-dependent parameters for Type B devices [17].

Mode	Base data rate (Gbps)				Modul.	Const.	Encoding	N_{TDS}
	$N_B = 1$	$N_B = 2$	$N_B = 3$	$N_B = 4$				
B0	0.794	1.588	2.381	3.175	SC	DBPSK	RS & Diff	2
B1	1.588	3.175	4.763	6.350	SC	DBPSK	RS & Diff	1
B2	3.175	6.350	9.526	**12.70**	SC	DQPSK	RS & Diff	1
B3	3.175	6.350	9.526	**12.70**	SC	UEP-QPSK	RS	1
B4	3.175	6.350	9.526	**12.70**	DAMI	N/A	RS	1

Table 2.11 Mode-dependent parameters for Type C devices [17].

Mode	Base data rate (Gbps)	Modul.	Const.	Encoding	N_{TDS}
C0	0.800	SC	OOK	RS	2
C1	1.600	SC	OOK	RS	1
C2	**3.200**	SC	4ASK	RS	1

denotes the number of tail bits. The table shows that by using four bonded channels, the ECMA-387 standard is capable of achieving data rates as high as 25 Gbps with mode A9.

Mode-dependent parameters for Type B and Type C devices and corresponding data rates for different channel bonding approaches are summarized in Table 2.10 and Table 2.11, respectively. While Type B devices can achieve data rates as high as 12.7 Gbps with four bonded channels, the maximum data rate with Type C devices is limited to 3.2 Gbps due to simplified architecture and inability to perform channel bonding.

In order to achieve interoperability, it is mandatory that all Type A devices support modes A0, B0, and C0 without channel bonding, while they may optionally support modes A0–A21 and B0–B3 with channel bonding, or modes C1–C2. All Type B devices, on the other hand, are required to support mode B0 with channel bonding, mode C0, and transmission of mode A0 (without channel bonding). Type B devices may optionally support modes C1 and C2. It is mandatory for Type C devices to support mode C0, while it is optional to support modes C1 and C2.

2.3.3.2 Timing-related and frame-related parameters

Timing-related parameters in ECMA-387 may vary depending on the device type and single-carrier versus multicarrier transmission method. Timing-related parameters for single-carrier transmissions in the ECMA-387 standard are summarized in Table 2.12 (see also Figure 2.9 and Figure 2.11), which include the SCBT of Type A devices, as well as Type B and Type C devices. The table shows that the timing-related parameters for single-carrier device types are mostly similar. Compared to Type B and Type C devices, an additional CP duration with four different possible sizes is included with SCBTs. On the other hand, a number of pilot and data symbols within an SC block of Type C devices may show variations owing to the use of time domain spreading.

The parameters for the OFDM mode of Type A devices are summarized in Table 2.13. A comparison of Table 2.13 with Table 2.12 reveals that while parameters such as the

Table 2.12 Timing-related parameters for SCBTs of Type A devices, and SC transmissions of Type B and Type C devices [17].

Param.	Description	SCBT (Type A)	SC (Type B)	SC (Type C)
f_{sym}	Symbol frequency	1.728 Gsps	1.728 Gsps	1.728 Gsps
T_{sym}	Symbol duration	0.5787 ns	0.5787 ns	0.5787 ns
N_B	Number of symbols per SCBT (or SC) block	256	256	$512N_{TDS}$
T_{SCBTB}	SCBT block interval	148.148 ns	N/A	N/A
N_D	Number of data symbols per SCBT (or SC) block	252	252	$508N_{TDS}$
N_P	Number of pilot symbols per SCBT (or SC) block	4	4	$4N_{TDS}$
N_{CP}	Number of symbols in the CP	0, 32, 64, 96	0	N/A
T_{CP}	CP duration	0 ns, 18.51 ns, 37.03 ns, 55.55 ns	0	N/A
N_{SCBTS}	Number of symbols per one SCBT symbol	256, 288, 320, 352	N/A	N/A
T_{SCBTS}	SCBT symbol interval	148.148 ns, 166.667 ns, 185.185 ns, 203.707 ns	N/A	N/A

Table 2.13 Timing-related parameters for OFDM transmissions of Type A devices [17].

Param.	Description	OFDM
f_{sym}	Symbol rate	2.592 Gsps
T_{sym}	Symbol time	0.386 ns
N_{FFT}	Number of subcarriers	512
T_{FFT}	FFT Period	197.53 ns
N_D	Number of data carriers	360
N_{DC}	Number of DC carriers	3
N_P	Number of pilot carriers	16
N_N	Number of null carriers	133
N_{CP}	Cyclic prefix length	64
T_{CP}	CP duration	24.70 ns
$T_{sym,OFDM}$	OFDM symbol duration	222.23 ns

symbol duration and the CP size show variations compared to the single carrier transmissions, there are also several other parameters specified for multicarrier transmissions, such as the FFT size and the number of DC/null carriers.

Frame-related parameters for SCBT and OFDM transmissions of Type A devices, Type B devices, and Type C devices are compared in Table 2.14, where the number of symbols in the ATS of Type A devices is given by

$$N_{ATS}^{(A)} = 256(N_{TXTS} + N_{RXTS})N_{DISCREP} , \quad (2.16)$$

Table 2.14 Frame-related parameters for ECMA-387 transmissions (all time units in nanoseconds) [17].

Param.	Description	SCBT	OFDM	SC (Type B)	SC (Type C)
N_{sync}	Number of symbols in FSS	2048	1792	2048	4096
T_{sync}	Duration of FSS	1185.19 ns	691.7 ns	1185.19 ns	2370.37 ns
N_{CE}	Number of symbols in CES	768	1088	768	1536
T_{CE}	Duration of CES	444.444 ns	419.97 ns	444.444 ns	888.89 ns
N_{prm}	Number of symbols in PLCP preamble	2816	2880	2816	5632
T_{prm}	Duration of frame preamble	1629.63 ns	1111.68 ns	1629.63 ns	3259.26 ns
N_{ATS}	Number of symbols in the ATS	$N_{ATS}^{(A)}$	$N_{ATS}^{(A)}$	$256N_{RXTS}$	N/A
T_{ATS}	Duration of the ATS	$N_{ATS}T_{sym}$	$N_{ATS}T_{sym}$	$N_{ATS}T_{sym}$	N/A
N_{frm}	Number of symbols in the frame	$N_{sync} + N_{hdr} + N_{pyl} + N_{ATS}$	$N_{prm} + N_{hdr} + N_{pyl} + N_{ATS}$	$N_{sync} + N_{hdr} + N_{pyl} + N_{ATS}$	$N_{prm} + N_{hdr} + N_{pyl}$
T_{frm}	Duration of the frame	$N_{frm}T_{sym}$	$N_{frm}T_{sym}$	$N_{frm}T_{sym}$	$N_{frm}T_{sym}$

with N_{TXTS} and N_{RXTS} denoting the numbers of training sequences for training the transmitter and receiver antennas, respectively, and $N_{DISCREP}$ denoting the different repetition factors specified in Table 2.8.[6] While the numbers of symbols in the frame synchronization sequence (FSS), channel estimation sequence (CES), and physical layer convergence protocol (PLCP) preamble are identical for SCBTs and Type B devices, Type C devices include twice the number of symbols for all these cases. OFDM transmissions have a relatively different set of parameters compared to other single-carrier devices. Since antenna training is not applicable to Type C devices, no ATS is specified for this device type.

2.4 IEEE 802.15.3c millimeter-wave radio standard

Another standard for high-rate communications at millimeter wave frequencies is the IEEE 802.15.3c standard (hereafter referred to as the 15.3c standard), which was completed in October 2009. The main application examples of the standard are portable point-to-point file transfer and video streaming. Unlike ECMA-387, which uses a distributed MAC protocol, the 15.3c standard uses a centralized MAC architecture.[7] Some important features of the MAC architecture include frame aggregation, beamforming, channel probing, and unequal error protection (UEP).

Both the 15.3c and the ECMA-387 standards use the first of the four channels specified in Table 2.5, which makes the harmonized coexistence of the standards with each other easier. As opposed to ECMA-387, channel bonding is not an option in the 15.3c standard. While a similar spectral mask as in the spectral mask of Type A and Type B devices in Figure 2.6 is utilized in 15.3c, the cut-off frequencies are slightly different, where

[6] ECMA-387 uses Frank–Zadoff (FZ) sequences for antenna training, frame synchronization, and channel estimation purposes.

[7] Note that the IEEE 802.15.3c standard is based on the former IEEE 802.15.3 (high-rate WPAN) and IEEE 802.15.3b (MAC amendment to IEEE 802.15.3-2003) standards.

$f_1 = 0.94$ GHz, $f_2 = 1.1$ GHz, $f_3 = 1.6$ GHz, and $f_4 = 2.2$ GHz. For OOK transmissions, up to 40 dB transmission power is allowed between $\pm f_0$, where $f_0 = 6$ MHz.

Two of the important and unique features in the 15.3c standard are the device discovery process and the aggregation of the MAC service data units (MSDUs) [19]. Due to directional beamformed transmissions, new protocols are required for beam discovery. Consider that a piconet controller (PNC) has $A_{\mathrm{T,PNC}}$ and $A_{\mathrm{R,PNC}}$ transmit and receive antennas, respectively, while a device has $A_{\mathrm{T,DEV}}$ and $A_{\mathrm{R,DEV}}$ transmit and receive antennas, respectively. Note that the number of transmit/receive antennas also specify the number of directions that a PNC or a device may transmit/receive. Then, for beam discovery purposes, the PNC transmits identical copies of beacons in $A_{\mathrm{T,PNC}}$ different directions. This enables devices in different locations to discover and join a certain piconet. Each device listens to the beacons of the PNC from $A_{\mathrm{R,DEV}}$ different directions. After comparing at least $A_{\mathrm{T,PNC}}$ and $A_{\mathrm{A,DEV}}$ pairs of transmit/receive directions, the device selects the pairs having the best and the second best link qualities and informs the PNC about these pairs. While a coarse beam is selected through this process, a second stage involves selection of a fine beam direction. Using a similar procedure as in the coarse beam selection, the best transmit/receive fine beam direction between the PNC and the device is determined, which is then used for data communications. Since the beam discovery process has a large overhead in terms of used packets that may otherwise be employed for communications, beam tracking can be utilized in slow fading channels. Beam tracking consumes considerably less time compared with beam discovery, because it selects the best beam pair within the already discovered coarse beam pair [19].

Another important feature of the 15.3c standard is the aggregation of the MSDUs and the block ACK procedure. The basic motivation for aggregation of the frames in the 15.3c standard is to improve the throughput using larger payload sizes. Two aggregation types are specified in the standard: (i) standard aggregation for high-speed data/video transmissions, and (ii) aggregation for low-latency bi-directional data transmission. Block ACKs are used only with aggregated frames; once the destination node receives the aggregated frames, it checks whether all the subframes are successfully received. For those subframes that are not correctly received, the corresponding bits in the block ACK bitmap field are set to zero, and a retransmission of those subframes is requested from the transmitter. The control of retransmission is different for the two different aggregation types, and the reader is referred to Section 8.8 of the 15.3c standard for further details [18].

The 15.3c standard defines a total of three PHY modes:

- single-carrier PHY (SC PHY);
- high-speed interface PHY (HSI PHY);
- audio/visual PHY (AV PHY).

As discussed in the previous section, the single-carrier transmission modes are more suitable for LOS scenarios, while the OFDM transmission is more appropriate for NLOS scenarios. At least one of the above three PHY modes is required to be implemented for each device complying with the standard. In the following sections, parameters related to modulation and coding schemes and transmitter architecture for these different PHY modes will be briefly reviewed.

Table 2.15 MCS dependent parameters for SC PHY MCS [18].

MCS class	MCS index	Data rate (Mbps), $L_p = 0$	Data rate (Mbps), $L_p = 64$	Modulation scheme	Spreading factor (L_{sf})	FEC type
Class 1	0 (CMS)	25.8	–	$\pi/2$ BPSK/	64	RS(255,239)
	1	412	361	(G)MSK	4	RS(255,239)
	2	825	722		2	RS(255,239)
	3 (MPR)	1650	1440		1	RS(255,239)
	4	1320	1160		1	LDPC(672,504)
	5	440	385		1	LDPC(672,336)
	6	880	770		1	LDPC(672,336)
Class 2	7	1760	1540	$\pi/2$ QPSK	1	LDPC(672,336))
	8	2640	2310		1	LDPC(672,504)
	9	3080	2700		1	LDPC(672,588)
	10	3290	2870		1	LDPC(1440,1344)
	11	3300	2890		1	RS(255,239)
Class 3	12	3960	3470	$\pi/2$ 8-PSK	1	LDPC(672,504)
	13	5280	4620	$\pi/2$ 16-QAM	1	LDPC(672,504)

2.4.1 Single-carrier PHY

SC-PHY in 15.3c is based on low-complexity single-carrier transmissions and it supports operation in both LOS and NLOS scenarios. It specifies three classes of modulation and coding schemes (MCSs) as illustrated in Table 2.15. Class 1 can achieve data rates as high as 1.5 Gbps and targets the low-power and low-cost mobile market with high data rate requirements [18]. Class 2 is capable of achieving twice the peak rate of Class 1, while Class 3 can achieve data rates above 5 Gbps. All the SC-PHY devices (except for the optional OOK/DAMI modes, which will not be discussed here) are required to implement the common mode signaling (CMS) MCS (mode 0) and the mandatory PHY rate (MPR) MCS (mode 3).[8] SC-PHY in 15.3c supports $\pi/2$ BPSK, $\pi/2$ QPSK, $\pi/2$ 8-PSK, and $\pi/2$ 16-QAM modulations, as well as the RS codes (mandatory) and LDPC block codes (optional) with several coding rates. The pilot word length is denoted by L_p, and the standard supports $L_p = 0, 8, 64$. In order to improve robustness, encoded bit sequences can be spread by different factors before mapping them onto different constellation diagrams. SC-PHY supports spreading factors of $L_{sf} = 64, 4, 2, 1$; for CMS mode, $L_{sf} = 64$ is employed to have reliable communications, which results in a peak data rate of only 25.8 Mbps.

Construction of the SC PHY payload in the 15.3c standard is shown in Figure 2.15. After scrambling of the MAC frame body and FEC encoding using RS or LDPC codes, stuff bits (i.e., bits carrying no information) are included in the scrambled and encoded

[8] Moreover, it is mandatory for all HSI-PHY and AV-PHY PNC capable devices to transmit a CMS interference mitigation sync frame in every superframe, and they should also be capable of receiving and decoding a CMS sync frame and other CMS command frames. This ensures that each PNC capable device is required to transmit a CMS sync frame within each superframe that is utilized for the mitigation of potential interference from other piconets.

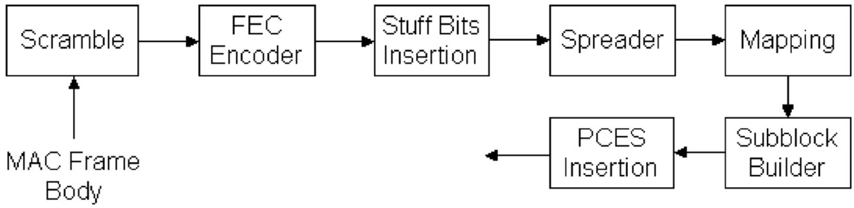

Figure 2.15 General transmitter structure for SC PHY in IEEE 802.15.3c [18].

Table 2.16 MCS-dependent parameters for HSI PHY [18].

MCS index	Data rate (Mbps)	Modulation scheme	Spreading factor (L_{sf})	Coding mode	FEC rate	
					msb 8b	lsb 8b
0	32.1	QPSK	48	EEP	1/2	
1	1540	QPSK	1	EEP	1/2	
2	2310	QPSK	1	EEP	3/4	
3	2695	QPSK	1	EEP	7/8	
4	3080	16-QAM	1	EEP	1/2	
5	4620	16-QAM	1	EEP	3/4	
6	5390	16-QAM	1	EEP	7/8	
7	5775	64-QAM	1	EEP	5/8	
8	1925	QPSK	1	UEP	1/2	3/4
9	2503	QPSK	1	UEP	3/4	7/8
10	3850	16-QAM	1	UEP	1/2	3/4
11	5005	16-QAM	1	UEP	3/4	7/8

MAC frame body. The reason for inclusion of stuff bits is that the length of the encoded data bits is typically not an integer multiple of the length of the data portion in a subblock. Then, Golay sequences with length 64 are used for spreading the intermediate bit sequence, thus improving the robustness of the frame header and the MAC frame body. The resulting bit sequences are then mapped to the desired constellation. Using pilot words that facilitate timing tracking, compensation for clock drift, and compensation for frequency offsets, subblocks are generated from constellation mappings. Frequency domain equalization also becomes possible through the use of pilot words, which act as a known cyclic prefix. As an optional stage, a pilot channel estimation sequence (PCES) can be inserted in the end in order for the receiver to reacquire the channel periodically.

2.4.2 High-speed interface PHY

HSI-PHY in 15.3c is based on the OFDM technology and is appropriate for low-latency bi-directional communications at high data rates, e.g., for an ad-hoc system which connects computers/devices in a conference room. As illustrated in Table 2.16, HSI-PHY supports QPSK, 16-QAM, and 64-QAM modulations, LDPC codes at different rates, and both EEP and UEP constellations (64-QAM is used with EEP only). When UEP is used, different coding rates are applied to the MSBs and LSBs, each of which

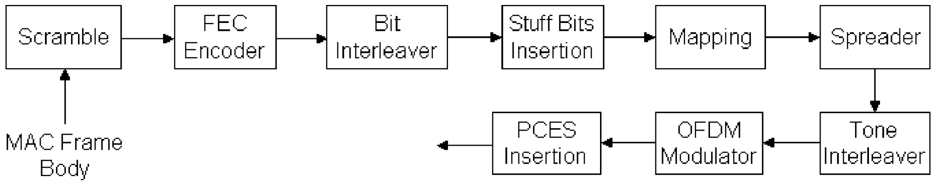

Figure 2.16 General transmitter structure for HSI PHY in IEEE 802.15.3c [18].

is composed of eight bits. Table 2.16 shows that the data rates achievable through HSI-PHY range from 32.1 Mbps to as high as 5.005 Gbps. The HSI-PHY uses 336 data subcarriers, 141 null subcarriers, 16 guard subcarriers, 16 pilot subcarriers, and 3 DC subcarriers.

The generation of the PHY payload in the HSI-PHY mode of 15.3c is shown in Figure 2.16. After scrambling, FEC encoding, bit interleaving, and stuff bit insertion, the bits are mapped onto one of the QPSK, 16-QAM, or 64-QAM constellations. The modulated complex values at the output of the constellation mapper are spread differently for the spreading factor $L_{sf} = 1$, and for $L_{sf} = 48$. For $L_{sf} = 1$, the outputs of the constellation mapper are grouped into sets of 336 complex numbers (corresponding to 336 data subcarriers), and each group is assigned to a certain OFDM symbol. For $L_{sf} = 48$, the outputs of the constellation mapper are grouped into sets of seven complex numbers, and each group is further spread by $L_{sf} = 48$ to obtain a block of 336 complex numbers. After the spreading operation, tone interleaving is applied to each block so that adjacent data symbols are mapped onto separated subcarriers. Finally, the interleaved complex numbers are mapped onto OFDM subcarriers, where the nth OFDM symbol can be expressed as

$$s_{k,n} = \frac{1}{\sqrt{N_{sc}}}\left[\sum_{m=0}^{N_D-1} d_{m,n} \exp\left(j2\pi\frac{kM_D(m)}{N_{sc}}\right) + x_n \sum_{m=0}^{N_P-1} p_{m,n} \exp\left(j2\pi\frac{kM_P(m)}{N_{sc}}\right)\right.$$
$$\left. + \sum_{m=0}^{N_G-1} g_{m,n} \exp\left(j2\pi\frac{kM_G(m)}{N_{sc}}\right)\right] \qquad (2.17)$$

where $k \in \{0, 1, \ldots, N_{FFT} - 1\}$, N_D is the number of data subcarriers, N_P is the number of pilot subcarriers, N_G is the number of guard subcarriers, N_{sc} is the number of total subcarriers, $d_{m,n}$, $p_{m,n}$, $g_{m,n}$ are the mth data, pilot, and guard subcarriers, respectively, placed on the nth OFDM symbol, and $M_D(m)$, $M_P(m)$, $M_G(m)$ are the mapping functions for data, pilot, and guard subcarriers, respectively.

2.4.3 Audio/visual PHY

The AV-OFDM mode in 15.3c is also based on OFDM transmission and is specifically designed for the streaming of uncompressed HD video. AV-OFDM includes two modes: high-rate PHY (HRP) and low-rate PHY (LRP). The data rates supported by HRP are summarized in Table 2.17, which shows that data rates as high as 3.8 Gbps are possible

Table 2.17 MCS-dependent parameters for AV PHY (HRP) [18].

MCS index	Data rate (Gbps)	Modulation	Inner code rate MSB	Inner code rate LSB	Coding Mode
0	0.952	QPSK	1/3	1/3	EEP
1	1.904	QPSK	2/3	2/3	EEP
2	3.807	16-QAM	2/3	2/3	EEP
3	1.904	QPSK	4/7	4/5	UEP
4	3.807	16-QAM	4/7	4/5	UEP
5	0.952	QPSK	1/3	N/A	MSB-only
6	1.904	QPSK	2/3	N/A	MSB-only

Table 2.18 MCS-dependent parameters for AV PHY (LRP) [18].

MCS index	Data rate (Mbps)	Modulation	FEC	Repetition
0	2.5	BPSK	1/3	8
1	3.8	BPSK	1/2	8
2	5.1	BPSK	2/3	8
3	10.2	BPSK	4/3	4

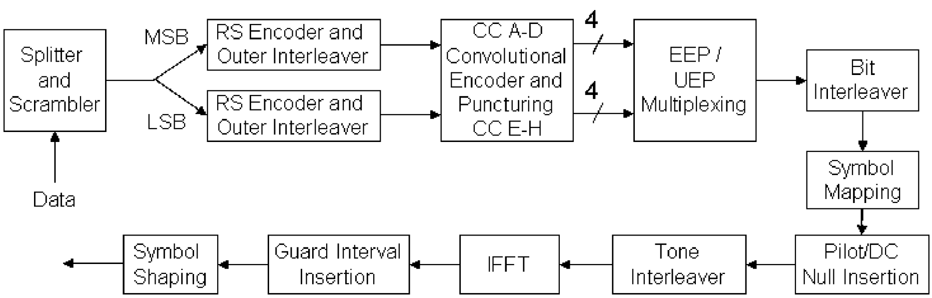

Figure 2.17 General transmitter structure for AV PHY in IEEE 802.15.3c (HRP) [18].

with AV-PHY. The HRP mode supports both EEP and UEP, and the modulation schemes of QPSK and 16-QAM. It also includes a transmission mode, where only the four MSBs are transmitted while the remaining four LSBs are discarded. The LRP mode, on the other hand, has a simpler architecture and it only supports considerably lower data rates. Table 2.18 shows that achievable data rates through LRP range between 2.5 Mbps and 10.2 Mbps. Only the BPSK modulation, FEC rates of 1/2, 1/3, and 2/3, and repetition rates of 4 and 8 are supported in the LRP mode.

HRP and LRP reference implementation block diagrams are shown in Figure 2.17 and Figure 2.18, respectively. For the HRP, the input data bits are scrambled and split into two bit streams. Then, RS codes with parameters (224, 216, $t = 4$) are used for the outer encoding of each stream, followed by the outer interleaver. After convolutional encoding and puncturing, multiple bit streams are multiplexed into a single stream and

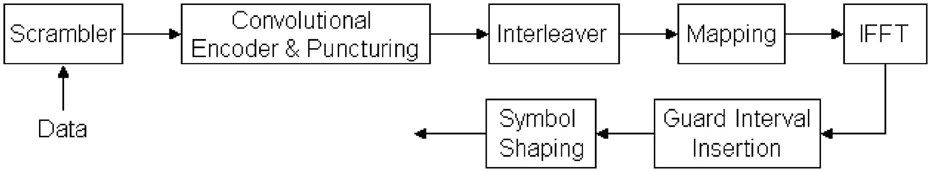

Figure 2.18 General transmitter structure for AV PHY in IEEE 802.15.3c (LRP) [18].

bit interleaving is applied. The output bit sequence is mapped onto one of the QPSK or 16-QAM constellations, and onto OFDM subcarriers after the insertion of pilot, DC, and null subcarriers, and tone interleaving. The LRP architecture in Figure 2.18 does not involve RS encoding, splitting/multiplexing, and UEP stages, and therefore has a considerably simpler architecture than the HRP, at the expense of limited capabilities.

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