

Chapter 2

OFDMA WiMAX Physical Layer

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Abstract IEEE 802.16 physical (PHY) layer is characterized by Orthogonal Frequency Division Multiplexing (OFDM), Time Division Duplexing, Frequency division Duplexing, Quadrature Amplitude Modulation and Adaptive Antenna Systems. After discussing the basics of OFDM and Orthogonal Frequency division Multiple Access (OFDMA), scalable OFDMA is presented and supported frequency bands, channel bandwidth and the different IEEE 802.16 PHY are discussed. The similarities and differences between wireless MAN-SC, wireless MAN-OFDM and wireless MAN-OFDMA PHY are finally highlighted.

2.1 Introduction

The IEEE 802.16 standard belongs to the IEEE 802 family, which applies to Ethernet. WiMAX is a form of wireless Ethernet and therefore the whole standard is based on the Open Systems Interconnections (OSI) reference model.

In the context of the OSI model, the lowest layer is the physical layer. It specifies the frequency band, the modulation scheme, error-correction techniques, synchronization between transmitter and receiver, data rate and the multiplexing techniques.

For IEEE 802.16, Physical layer was defined for a wide range of frequencies from 2–66 GHz. In sub frequency range of 10–66 GHz there essentially is LoS propagation. Therefore, single carrier modulation was chosen, because of low

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system complexity. Downlink channel is shared among users with TDM signals. Subscriber unit are being allocated individual time slots. Access in uplink is being realized with TDMA. In the 2–11 GHz bands, communications can be achieved for licensed and non-licensed bands. The communication is also available in NLoS conditions.

To ensure the most efficient delivery in terms of bandwidth and available frequency spectrum, the IEEE 802.16 physical layer uses a number of legacy technologies. These technologies include Orthogonal Frequency Division Multiplexing (OFDM), Time Division Duplexing (TDD), Frequency Division Duplexing (FDD), Quadrature Amplitude Modulation (QAM), and Adaptive Antenna System (AAS). The WiMAX physical layer is based on OFDM. OFDM is the transmission scheme of choice to enable high speed data, video, and multimedia communications and presently, besides WiMAX, it is used by a variety of commercial broadband systems, including DSL, Wi-Fi, Digital Video Broadcast-Handheld (DVB-H).

Above the physical layer are the functions associated with providing service to subscribers. These functions include transmitting data in frames and controlling access to the shared wireless medium, and are grouped into a media access control (MAC) layer.

This Chapter is organized as follows. [Section 2.2](#) addresses the history, evolution and applications of OFDM. [Section 2.3](#) presents the OFDM fundamentals by comparing it with FDMA as well as describing OFDM signal characteristics. [Section 2.4](#) describes the concepts behind OFDM transmission and presents the serial to parallel converter as well as the OFDM demodulator. The OFDM symbol is described in [Section 2.5](#) while [Section 2.6](#) presents ISI and ICI mitigation. [Section 2.7](#) addresses spectral efficiency. [Section 2.8](#) presents the improvements of OFDMA and the advantages of subchannelisation. [Section 2.9](#) and [2.10](#) present the advantages and disadvantages of OFDM systems. The details on scalable OFDMA are presented in [Section 2.11](#), including the parameters, principles, and the reference model. [Section 2.12](#) addresses specific issues of PHY layer, including WirelessHUMAN PHY, while [Section 2.13](#) addresses WirelessMAN-SC (single carrier) PHY. [Section 2.14](#) covers WirelessMAN-OFDM PHY while [Section 2.15](#) describes WirelessMAN-OFDMA PHY. Finally, [Section 2.16](#) presents the conclusions.

2.2 History and Development of OFDM

2.2.1 Evolution

OFDM has recently been gaining interest from telecommunications industry. It has been chosen for several current and communications systems all over the world. Nevertheless, OFDM had a long history of existence ([Table 2.1](#)). The first multichannel modulation systems appeared in the 1950s as frequency division multiplexed

Table 2.1 A brief history of OFDM

Dates	OFDM Landmark Achieved
1966	Chang postulated the principle of transmitting messages simultaneously through a linear band limited channel without ICI and ISI [3]. This is considered the first official publication on multicarrier modulation. Earlier work on OFDM was Holsinger's 1964 MIT dissertation [4] and some of Gallager's early work on waterfilling [5].
1967	Saltzberg observed that, in order to increase efficiency of parallel system, cross talk between adjacent channels should be reduced [6].
1971	Weinstein and Ebert show that multicarrier modulation can be accomplished by using a DFT [7].
1980	Peled and Ruiz introduced use of Cyclic Prefix (CP) or cyclic extension instead of guard spaces [8].
1985	Cimini at Bell Labs identifies many of the key issues in OFDM transmission and does a proof-of-concept design [9].
1990–1995	OFDM was exploited for wideband data communications over mobile radio FM radio, DSL, HDSL, ADSL and VDSL. First commercial use of OFDM in DAB and DVB.
1999	The IEEE 802.11 used OFDM at the physical layer. HiperLAN and HiperLAN/2 also adopted OFDM at the physical layer.
2002	The IEEE 802.16 committee released WMAN standard 802.16 based on OFDM.
2003	The IEEE 802.11 committee releases the 802.11g standard for operation in the 2.4 GHz band. The multiband OFDM standard for ultra wideband is developed.
2004	OFDM is candidate for IEEE 802.15.3a standard for wireless PAN (MB-OFDM) and IEEE 802.11n standard for next generation wireless LAN [33].
2005	OFDMA is candidate for the 3GPP Long Term Evolution (LTE) air interface E-UTRA downlink [33].
2007	The first complete LTE air interface implementation was demonstrated, including OFDM-MIMO, SC-FDMA and multi-user MIMO uplink [34].
2008	Mobile WiMAX base stations and subscriber devices were first certified by WiMAX Forum.

military radio links. OFDM had been used by US military in several high frequency military systems, such as KINEPLEX, ANDEFT and KATHRYN [1, 2].

In December 1966, Robert W. Chang outlined first OFDM scheme. This was a theoretical way to transmit simultaneous data stream through linear band limited channel without Inter Symbol Interference (ISI) and Inter Carrier Interference (ICI). Chang obtained the first US patent on OFDM in 1970 [12]. Around the same time, Saltzberg performed an analysis of the performance of the OFDM system and concluded that the strategy should concentrate more on reducing cross talk between adjacent channels than on perfecting the channels [6].

Until this time, we needed a large number of subcarrier oscillators to perform parallel modulations and demodulations. This was the main reason why the OFDM technique has taken a long time to become a prominence. It was difficult to generate such a signal, and even harder to receive and demodulate the signal. The hardware solution, which makes use of multiple modulators and demodulators, was somewhat impractical for use in the civil systems.

In the year 1971, Weinstein and Ebert used Discrete Fourier Transform (DFT) to perform baseband modulation and demodulation. The use of DFT eliminated the

need for bank of subcarrier oscillators. These efforts paved the way for the way for easier, more useful and efficient implementation of the system. The availability of this technique, and the technology that allows it to be implemented on integrated circuits at a reasonable price, has permitted OFDM to be developed as far as it has. The process of transforming from the time domain representation to the frequency domain representation uses the Fourier transform itself, whereas the reverse process uses the inverse Fourier transform.

All the proposals until this moment in time used guard spaces in frequency domain and a raised cosine windowing in time domain to combat ISI and ICI. Another milestone for OFDM history was when Peled and Ruiz introduced Cyclic Prefix (CP) or cyclic extension in 1980 [8]. This solved the problem of maintaining orthogonal characteristics of the transmitted signals at severe transmission conditions. The generic idea that they placed was to use cyclic extension of OFDM symbols instead of using empty guard spaces in frequency domain. This effectively turns the channel as performing cyclic convolution, which provides orthogonality over dispersive channels when CP is longer than the channel impulse response [1]. It is obvious that introducing CP causes loss of signal energy proportional to length of CP compared to symbol length but, in turn, it facilitates a zero ICI advantage which pays off.

By this time, inclusion of FFT and CP in OFDM system and substantial advancements in Digital Signal Processing (DSP) technology made it an important part of telecommunications landscape. In the 1990s, OFDM was exploited for wideband data communications over mobile radio FM channels, High-bit-rate Digital Subscriber Lines (HDSL at 1.6 Mbps), Asymmetric Digital Subscriber Lines (ADSL up to 6 Mbps) and Very-high-speed Digital Subscriber Lines (VDSL at 100 Mbps).

The first commercial use of OFDM technology was made in Digital Audio Broadcasting (DAB). The development of DAB started in 1987 and was standardized in 1994. DAB services started in 1995 in UK and Sweden.

The development of Digital Video Broadcasting (DVB) was started in 1993. DVB along with High-Definition TeleVision (HDTV) terrestrial broadcasting standard was published in 1995. At the dawn of the twentieth century, several Wireless Local Area Network (WLAN) standards adopted OFDM on their physical layers. Development of European WLAN standard HiperLAN started in 1995. HiperLAN/2 was defined in June 1999 which adopts OFDM in physical layer.

OFDM technology is also well positioned to meet future needs for mobile packet data traffics. It is emerging as a popular solution for wireless LAN, and also for fixed broad-band access. OFDM has successfully replaced DSSS for 802.11a and 802.11g. Perhaps of even greater importance is the emergence of this technology as a competitor for future fourth Generations (4G) wireless systems. These systems, expected to emerge by the year 2010, promise to at last deliver on the wireless ‘Nirvana’ of anywhere, anytime, anything communications [14]. It is expected that OFDM will become the chosen technology in most wireless links worldwide [13] and it will certainly be implemented in 4G radio mobile systems.

Table 2.2 Wireless systems using OFDM [10]

Application	WMAN	WLAN	WPAN
Technology	OFDM	OFDM	OFDM
Cell Radius	1–20 km	up to 300 m	few tens of meter
Mobility	High and low	Low	very low
Freq Band	2–66 GHz	2–5 GHz	5–10 GHz
Data Rate	Few Mbps	up to 100 Mbps	up to 10 Mbps
Deployment	IEEE 802.16a, d, e, WiMAX, 3GPP-LTE	IEEE 802.11a, g, HiperLAN2	IEEE 802.15, Zig-Bee

2.2.2 Applications of OFDM

OFDM has been incorporated into four basic applications: (1) Digital Audio Broadcasting (DAB); (2) Digital Video Broadcasting (DVB), over the terrestrial network Digital Terrestrial Television Broadcasting (DTTB); (3) Magic WAND (Wireless ATM Network Demonstrator); and (4) IEEE 802.11a/HiperLAN2 and MMAC WLAN Standards.

DAB and DVD were the first standards to use OFDM. Next Magic WAND was introduced, which demonstrated the viability of OFDM. Lastly, and most importantly, the most recent 5 GHz applications evolved which were the first to use OFDM in packet-based wireless communications. Few of the OFDM application and their details based on the type of wireless access technique are summarized in Table 2.2.

2.3 OFDM Fundamentals

2.3.1 OFDM Versus FDM

Orthogonal Frequency Division Multiplexing is an advanced form of Frequency Division Multiplexing (FDM) where the frequencies multiplexed are orthogonal to each other and their spectra overlap with the neighbouring carriers. As shown in the Fig. 2.1 the subcarriers never overlap for FDM. In contrast to FDM, OFDM is based on the principle of overlapping orthogonal sub carriers.

The spectral efficiency of OFDM system as compared to FDMA is depicted in the Fig. 2.2. The overlapping multicarrier technique can achieve superior bandwidth utilization. There is a huge difference between the conventional non-overlapping multicarrier techniques such as FDMA and the overlapping multicarrier technique such as OFDM.

In frequency division multiplex system, many carriers are spaced apart. The signals are received using conventional filters and demodulators. In these receivers guard bands are introduced between each subcarriers resulting into reduced spectral efficiency. But in an OFDM system it is possible to arrange the carriers in such a

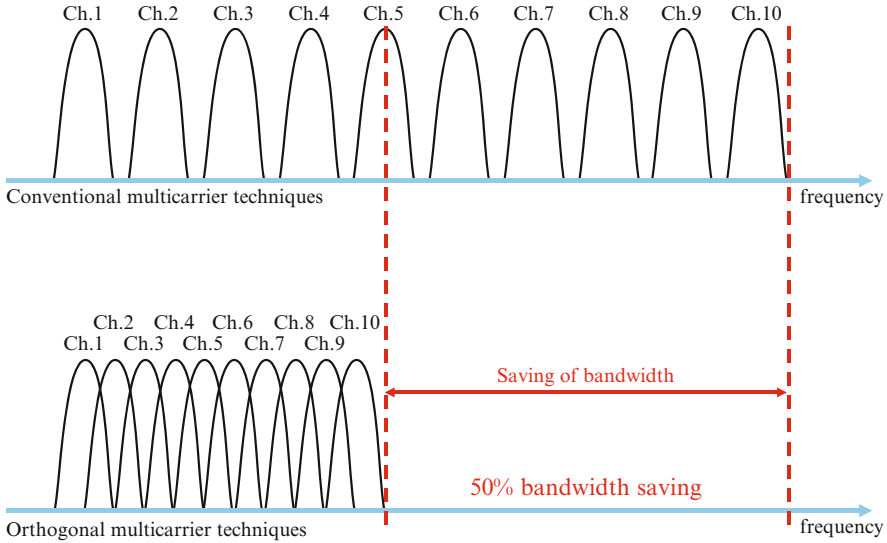


Fig. 2.1 Concept of OFDM signal

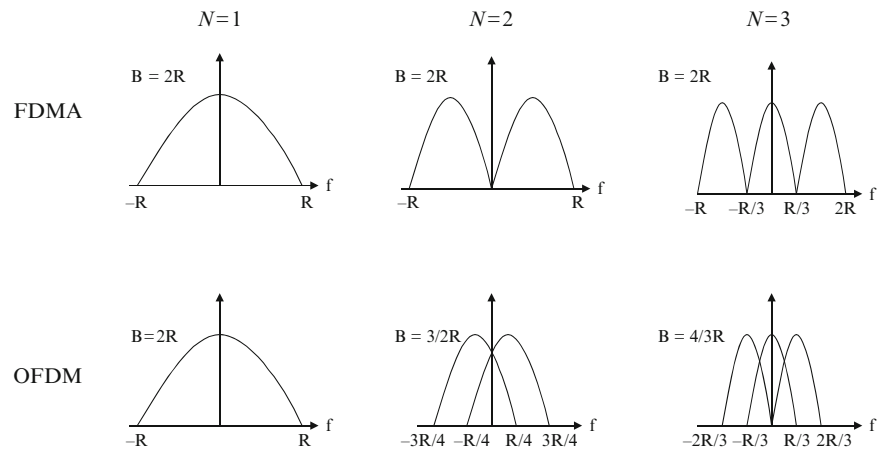


Fig. 2.2 Spectrum efficiency of OFDM compared to FDMA

fashion that the sidebands of the individual subcarriers overlap and the signals are still received without adjacent carrier interference. The main advantage of this concept is that each of the radio streams experiences almost flat fading channel. In slowly fading channels the inter-symbol interference (ISI) and inter-carrier interference(ICI) is avoided with a small loss of energy using cyclic prefix.

In order to assure a high spectral efficiency the subchannel waveforms must have overlapping transmit spectra. But to have overlapping spectra, subchannels need to

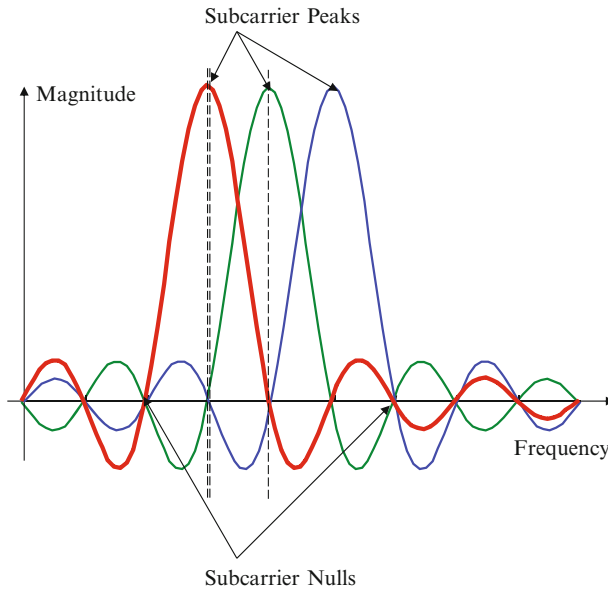


Fig. 2.3 Orthogonal subcarriers in multicarrier systems (OFDM)

be orthogonal. Orthogonality is a property that allows the signals to be perfectly transmitted over a common channel and detected without interference. Loss of orthogonality results in blurring between the transmitted signals and loss of information. For OFDM signals, the peak of one sub carrier coincides with the nulls of the other sub carriers. This is shown in Fig. 2.3. Thus there is no interference from other sub carriers at the peak of a desired sub carrier even though the sub carrier spectrums overlap. OFDM system avoids the loss in bandwidth efficiency prevalent in system using non orthogonal carrier set.

2.3.2 OFDM Signal Characteristics

An OFDM signal consists of N orthogonal subcarriers modulated by N parallel data streams, Fig. 2.4. The data symbols ($d_{n,k}$) are first assembled into a group of block size N and then modulated with complex exponential waveform $\{\phi_k(t)\}$. After modulation they are transmitted simultaneously as transmitter data stream.

The total continuous-time signal consisting of OFDM block is given by

$$x(t) = \sum_{n=-\infty}^{\infty} \left[\sum_{k=0}^{N-1} d_{n,k} \varphi_k(t - nT_d) \right] \quad (2.1)$$

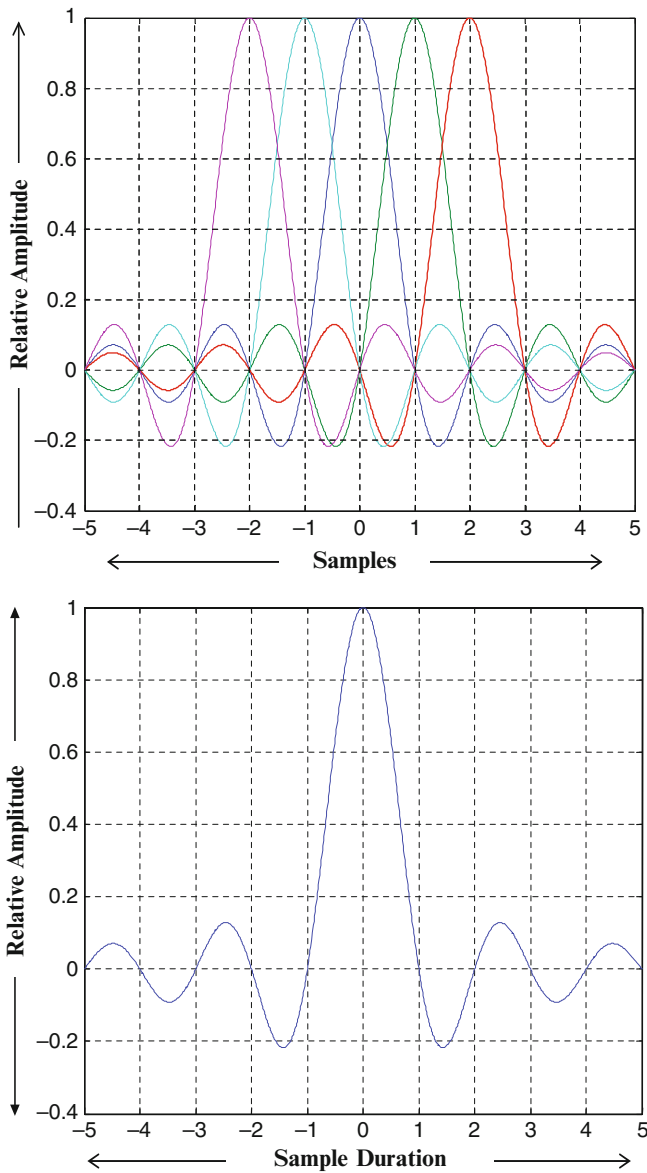


Fig. 2.4 Spectra for OFDM subcarriers

where, $\phi_k(t)$ represents each baseband subcarrier and is given by

$$\varphi_k(t) = \begin{cases} e^{j2\pi f_k t} & t \in [0, T_d] \\ 0 & \text{otherwise} \end{cases} \quad (2.2)$$

where $d_{n,k}$ is the symbol transmitted during n_{th} timing interval using k_{th} subcarrier, T_d is the symbol duration, N is the number of OFDM subcarriers and f_k is k^{th} subcarrier frequency, which is calculated as $f_k = f_o + \frac{k}{T_d}$, $k = 0 \dots N - 1$. Note that f_o is the lowest frequency used.

2.4 OFDM Transmission

2.4.1 Concept

The OFDM based communication systems transmit multiple data symbols simultaneously using orthogonal subcarriers. The principle behind the OFDM system is to decompose the high data stream of bandwidth W into N lower rate data streams and then to transmit them simultaneously over a large number of subcarriers. Value of N is kept sufficiently high to make the individual bandwidth (W/N) of subcarriers narrower than the coherence bandwidth (B_c) of the channel. The flat fading experienced by the individual subcarriers is compensated using single tap equalizers. These subcarriers are orthogonal to each other which allows for the overlapping of the subcarriers. The orthogonality ensures the separation of subcarriers at the receiver side. As compared to FDMA systems, which do not allow spectral overlapping of carriers, OFDM systems are more spectrally efficient.

OFDM transmitter and receiver systems are described in Figs. 2.5 and 2.6. At the transmitter, the signal is defined in the frequency domain. Forward Error Control/Correction (FEC) coding and interleaving block is used to obtain the robustness needed to protect against burst errors.

The modulator transforms the encoded blocks of bits into a vector of complex values, Fig. 2.7. Group of bits are mapped onto a modulation constellation producing a complex value and representing a modulated carrier. The amplitudes and phases of the carriers depend on the data to be transmitted. The data transitions are synchronized at the carriers, and may be processed together, symbol by symbol.

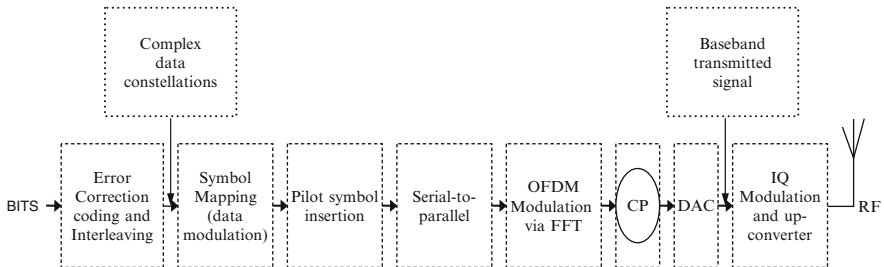


Fig. 2.5 OFDM transmitter

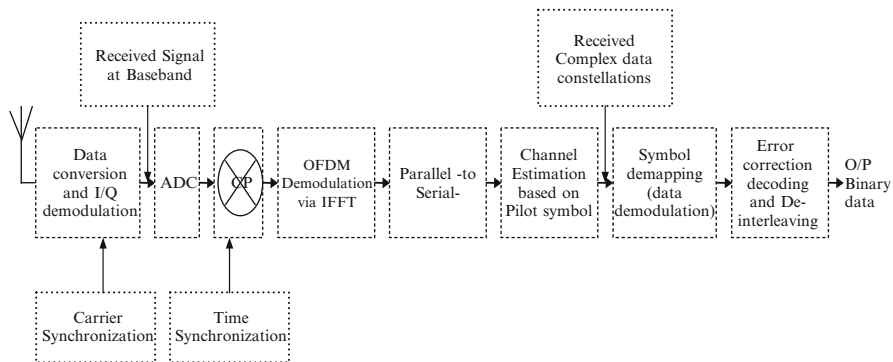


Fig. 2.6 OFDM receiver

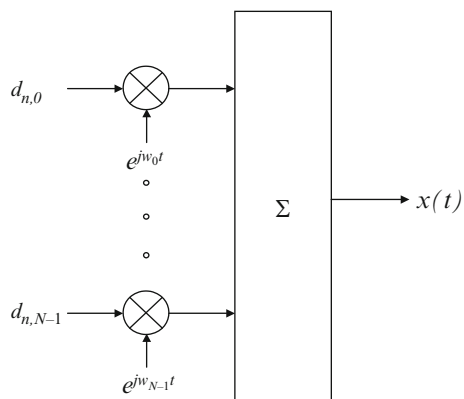


Fig. 2.7 OFDM modulator

As the OFDM carriers are spread over a frequency range, chances are there that some frequency selective attenuation occurs on a time varying basis. A deep fade on a particular frequency may cause the loss of data on that frequency for that given time, thus some of the subcarriers can be strongly attenuated and that will cause burst errors. In these situations, FEC in COFDM can fix the errors [15]. An OFDM system with addition of channel coding and interleaving is referred to as Coded OFDM (COFDM). An efficient FEC coding in flat fading situations leads to a very high coding gain. In a single carrier modulation, if such a deep fade occurs, too many consecutive symbols may be lost and FEC may not be too effective in recovering the lost data.

In a digital domain, binary input data is collected and FEC coded with schemes such as convolutional codes. The coded bit stream is interleaved to obtain diversity gain. Afterwards, a group of channel coded bits are gathered together (1 for BPSK, 2 for QPSK, 4 for QPSK, etc.) and mapped to the corresponding constellation points.

2.4.2 Serial to Parallel Converter

Data to be transmitted is typically in the form of a serial data stream. Serial to parallel conversion block is needed to convert the input serial bit stream to the data to be transmitted in each OFDM symbol. The data allocated to each symbol depends on the modulation scheme used and the number of subcarriers. For example, in case a subcarrier modulation of 16-QAM each subcarrier carries 4 bits of data, and so for a transmission using 100 subcarriers the number of bits per symbol would be 400.

During symbol mapping the input data is converted into complex value constellation points, according to a given constellation. Typical constellations for wireless applications are, BPSK, QAM, and 16 QAM. The amount of data transmitted on each subcarrier depends on the constellation. Channel condition is the deciding factor for the type of constellation to be used. In a channel with high interference a small constellation like BPSK is favourable as the required signal-to-noise-ratio (SNR) in the receiver is low. For interference free channel a larger constellation is more beneficial due to the higher bit rate. Known pilot symbols mapped with known mapping schemes can be inserted at this moment.

Cyclic prefix is inserted in every block of data according to the system specification and the data is multiplexed to a serial fashion. At this point of time, the data is OFDM modulated and ready to be transmitted.

A Digital-to-Analogue Converter (DAC) is used to transform the time domain digital data to time domain analogue data. RF modulation is performed and the signal is up-converted to transmission frequency. After the transmission of OFDM signal from the transmitter antenna, the signals go through all the anomaly and hostility of wireless channel. After the receiving the signal, the receiver down-converts the signal; and converts to digital domain using Analogue-to-Digital Converter (ADC). At the time of down-conversion of received signal, carrier frequency synchronization is performed. After ADC conversion, symbol timing synchronization is achieved. An FFT block is used to demodulate the OFDM signal. After that, channel estimation is performed using the demodulated pilots. Using the estimations, the complex received data is obtained which are de-mapped according to the transmission constellation diagram. At this moment, FEC decoding and de-interleaving are used to recover the originally transmitted bit stream.

OFDM is tolerant to multi path interference. A high peak data rate can be achieved by using higher order modulations, such as 16 QAM and 64 QAM, which improve the spectral efficiency of the system.

2.4.3 Demodulator

The OFDM demodulator is shown in the form of a simplified block diagram is shown in Fig. 2.8. The orthogonality condition of the signals is based orthogonality of subcarriers $\{\phi_k(\tau)\}$, defined by:

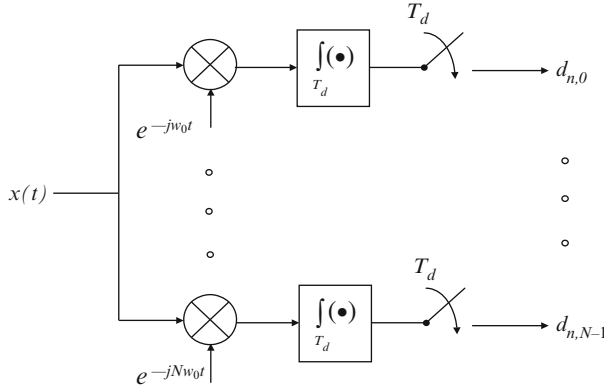


Fig. 2.8 OFDM demodulator

$$\int_{\mathbb{R}} \varphi_k(t) \varphi_l^*(t) dt = T_d \delta(k - l) = \begin{cases} T_d & k = l \\ 0 & \text{otherwise} \end{cases} \quad (2.3)$$

The demodulator satisfies the above condition for orthogonality of the subcarriers.

2.5 OFDM Symbol Description

OFDM boosts throughput by using several subcarriers in parallel while multiplexing data over the set of subcarriers. Inverse-Fourier-transforming (IFT) creates the OFDM waveform. This time duration is referred to as the useful symbol time T_{sym} . A copy of the last TCP of the useful symbol period, termed Cyclic Prefix (CP), is used to mitigate multipath, while maintaining the orthogonality of the tones. Figure 2.9 illustrates this structure in the time domain.

The frequency domain description includes the basic structure of an OFDM symbol (Fig. 2.10).

An OFDM symbol shown in Fig. 2.9 is made up from subcarriers, the number of which determines the FFT size used. There are three subcarrier types: (1) **data subcarriers**, for data transmission, (2) **pilot subcarriers**, for various estimation purposes, and (3) **null subcarriers**, for no transmission at all, for guard bands, non-active subcarriers and for the DC subcarrier.

2.6 ISI and ICI Mitigation

Two types of difficulties arise when a signal is transmitted through a time-dispersive channel. First, channel dispersion destroys the orthogonality between subcarriers and cause intercarrier interference (ICI) for the signal. Second, the

Fig. 2.9 OFDM symbol time structure (From [19])

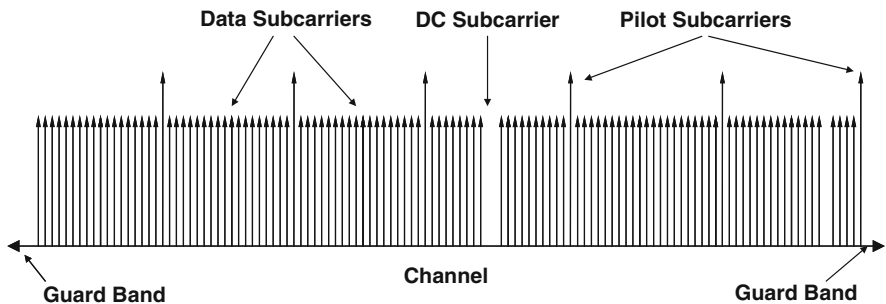
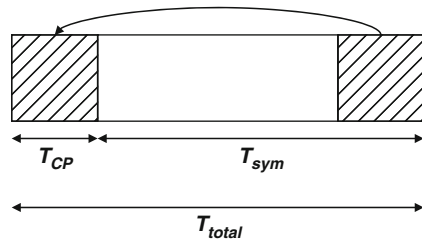


Fig. 2.10 OFDM frequency description (From [20])

system may sometimes transmit multiple OFDM symbols in a series causing intersymbol interference (ISI) between successive OFDM symbols. Guard intervals were proposed as the solution. A guard interval is defined by an empty space between two OFDM symbols, which serves as a buffer for the multipath reflection. When guard bands are inserted between successive OFDM symbols avoids ISI but cannot cope with the loss of the subcarrier orthogonality.

This problem was addressed by Peled and Ruiz, in 1980, by introducing cyclic prefix (CP) instead of guard interval between successive OFDM symbols. CP is a copy of the last part of OFDM symbol which is appended to front the transmitted OFDM symbol. The cyclic prefix preserves the orthogonality of the subcarriers and prevents ISI between successive OFDM symbols. CP helps to maintain orthogonality between the sub carriers. The interval must be chosen to be larger than the expected maximum delay spread, such that multi path reflection from one symbol would not interfere with another.

As shown in the Fig. 2.11, CP still occupies the same time interval as guard period but, in turn, ensures that the delayed replicas of the OFDM symbols will always have a complete symbol within the FFT interval. Thus, the transmitted signal is still periodic and this periodicity plays a very significant role as this helps maintaining the orthogonality. In a Fourier transform, all the resultant components of the original signal are orthogonal to each other. CP makes sure that subsequent subcarriers are orthogonal to each other.

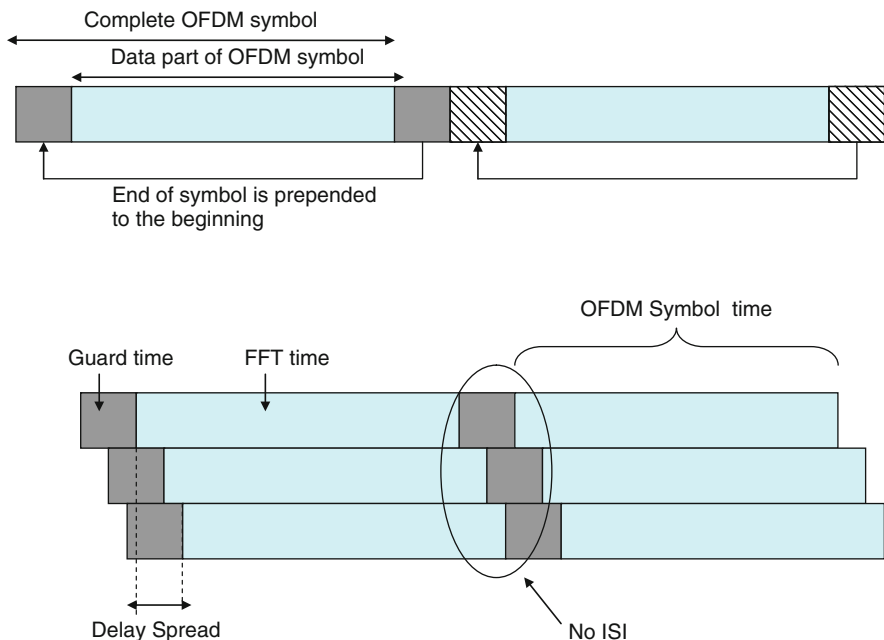


Fig. 2.11 Use of cyclic prefix to combat ISI and ICI

At the receiver side, CP is removed before any processing starts. As long as the length of CP interval is larger than maximum expected delay spread, all reflections of previous symbols are removed and orthogonality is restored. The orthogonality is lost when the delay spread is larger than length of CP interval.

Although the generated signals are always orthogonal, inserting CP has its own cost. Part of signal energy is lost since it carries no information. The loss may be calculated by

$$SNR_{loss_CP} = -10\log_{10}\left(1 - \frac{T_{CP}}{T_{sym}}\right) \quad (2.4)$$

where T_{CP} is the interval length of CP and T_{sym} is the OFDM symbol duration.

The total symbol duration is

$$T_{total} = T_{CP} + T_{sym}. \quad (2.5)$$

The advantage gained by introducing CP is the zero ICI and ISI (although part of the signal energy is lost). Thus, CP combats two main problems of signal transmission, first it removes the effect of ISI, and second, by maintaining orthogonality, it completely removes the ICI.

2.7 Spectral Efficiency

Figure 2.2 illustrates the difference between FDMA and OFDM systems. In the case of OFDM, a higher better spectral efficiency is achieved by maintaining orthogonality between the subcarriers. If orthogonality is maintained between different subchannels during transmission, then it is possible to separate the signals very easily at the receiver side. This is ensured by classical FDM by inserting guard bands between sub channels. These guard bands keep the subchannels far enough so that separation of different subchannels is possible. Naturally, inserting guard bands results to inefficient use of spectral resources.

In OFDM, orthogonality makes it possible in OFDM to arrange the subcarriers in such a way that the sidebands of the individual carriers overlap and still the signals are received at the receiver without being interfered by ICI. The receiver acts as a bank of demodulators, translating each subcarrier down to DC, with the resulting signal integrated over a symbol period to recover raw data. If the other subcarriers all down converted to the frequencies that, in the time domain, have a whole number of cycles in a symbol period T_{sym} , then the integration process results in zero contribution from all other carriers. As a consequence, the subcarriers are linearly independent (i.e., orthogonal) if the carrier spacing is a multiple of $1/T_{sym}$ [18].

2.8 Orthogonal Frequency Division Modulation Access

2.8.1 Improvements

In the previous section, we discussed the OFDM as a multiplexing scheme that provides better spectral efficiency and immunity to multipath fading. The OFDM system is also simpler to design based on FFT/IFFT method. These advantages are further extended for multiple access schemes by assigning a subset of subcarriers or tones of OFDM to individual users. This multiple access technique is termed as OFDMA. The allocation of subsets of tones to various users allows for simultaneous transmission of data from multiple users, allowing for sharing the physical medium. Although this technique looks very much like FDMA, the large guard bands required in FDMA are not needed in OFDMA.

2.8.2 Subchannelization

In OFDMA, the active subcarriers are divided into subsets of subcarriers. Each subset represents a subchannel, as shown in the Fig. 1.2. These sub-carriers that

form a single subchannel need not be adjacent. Thus, an OFDM symbol is subdivided into several subchannels by grouping the subcarriers. In the DL, a single subchannel may be intended for different receivers whereas, in the uplink, a transmitter may be assigned one or more subchannels, and several transmitters may transmit simultaneously.

2.8.3 OFDMA Subchannelization: Its advantages to WiMAX

In OFDMA, subchannelization defines subchannels that can be allocated to subcarrier stations depending on their channel conditions and data requirements. Several SS can transmit in the same time slot over several subchannels. Depending on the channel conditions and data requirements modulation and coding is set individually for each subscriber. The transmitter power can be adapted separately as well, which optimizes the use of network resources. Because of subchannelization OFDMA signals are more complex than OFDM ones but offer better performance and scalability. This feature is very useful for WiMAX BSs. By using subchannelization, within the same time slot, the BS is able to allocate more transmitter power to those SSs with lower SNR and less power to the ones with higher SNR . Subchannelization also enables the BS to allocate higher power to subchannels assigned to indoor SSs, which results in better in-building coverage.

Subchannelization in the uplink saves the power of the user device by concentrating power to the selected subchannels allocated to it. This power saving feature is indeed very useful for battery powered SSs.

Subchannelisation uses orthogonal frequency-division multiple access with a 2048-point transform [11] and is designed for NLoS operation in the frequency bands below 11 GHz. For licensed bands, channel bandwidths allowed is limited to the regulatory provisioned bandwidth divided by any power of 2 no less than 1.0 MHz. The concept is shown in Fig. 2.12.

2.9 Advantages of OFDM Systems

The following advantages of OFDM may be identified:

- OFDM is spectrally efficient; IFFT/FFT operation ensures that sub-carriers do not interfere with each other.
- OFDM has an inherent robustness against narrowband interference. Narrowband interference will affect at most a couple of subchannels. Information from the affected subchannels can be erased and recovered via the forward error correction (FEC) codes.
- Equalization is very simple compared to Single-Carrier systems.

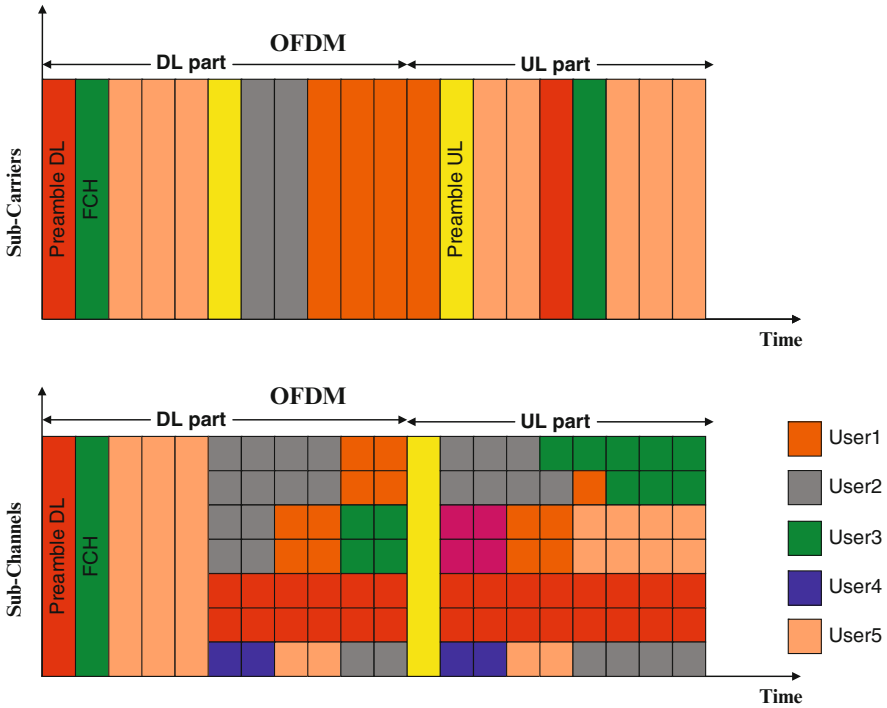


Fig. 2.12 OFDMA versus OFDM: subchannels and sub-carriers

- The OFDM transmitter is low cost as the design is simple because the modulation technique is simpler implementation based on a highly optimized FFT/IFFT block. Also OFDM transmitters possess the ability to implement the mapping of bits to unique carriers via the use of the Inverse Fast Fourier Transform (IFFT) [13].
- As the OFDM transmitter simplifies the channel effect, thus a simple receiver structure is enough for recovering transmitted data. If we use coherent modulation schemes, then very simple channel estimation (and/or equalization) is needed. In turn, no channel estimator is needed if differential modulation schemes are used [14].
- In a relatively slow time-varying channel, it is possible to significantly enhance the capacity by adapting the data rate per subcarrier according to the value of SNR for that particular subcarrier [1].
- In contrast to CDMA, OFDM receiver collects signal energy in frequency domain, thus it is able to protect energy loss at frequency domain.
- OFDM is more resistant to frequency selective fading than single carrier systems.
- The orthogonality preservation procedures in OFDM are much simpler compared to CDMA or TDMA techniques even in very severe multipath conditions.

- OFDM can be used for high-speed multimedia applications with lower service cost.
- OFDM can also support dynamic packet access.
- Ability to comply with world-wide regulations: Bands and tones can be dynamically turned on/off to comply with changing regulations. Single frequency networks are possible in OFDM, which is especially attractive for broadcast applications.
- Smart antennas can be integrated with OFDM. MIMO systems and space-time coding can be realized on OFDM and all the benefits of MIMO systems can be obtained easily. Adaptive modulation and tone/power allocation are also realizable on OFDM.

2.10 Disadvantages of OFDM Systems

2.10.1 *Strict Synchronization Requirement*

OFDM is highly sensitive to time and frequency synchronization errors, especially at frequency synchronization errors, everything can go wrong. Demodulation of an OFDM signal with an offset in the frequency can lead to a high bit error rate. These are two sources of synchronization errors. One is caused by the difference between local oscillator frequencies in transmitter and receiver, while the other is due to the relative motion between the transmitter and receiver that gives Doppler spread. Local oscillator frequencies at both points must match as closely as they can. For higher number of subchannels, the matching should be even more perfect. Motion of transmitter and receiver causes the other frequency error. So, OFDM may show significant performance degradation at high-speed moving vehicles [12]. To optimize the performance of an OFDM link, accurate synchronization is therefore of prime importance.

Synchronization needs to be done into three aspects: symbol, carrier frequency and sampling frequency synchronization. A description of synchronization procedures is given in [1].

2.10.2 *Peak-to-Average Power Ratio*

Peak to Average Power Ratio (PAPR) is proportional to the number of subcarriers used for OFDM systems. The PAPR for an OFDM system is given by $10 \log(N)$ where N is the number of subcarriers. For example for a 48 subcarrier system, such as 802.11a where 48 out of 64 subcarriers are active, the PAPR is approximately 17 dB. Therefore OFDM system with large number of sub-carriers will thus have a very large PAPR when the sub-carriers add up coherently. An

Large PAPR of a system makes the implementation of Digital-to-Analog Converter (DAC) and Analog-to-Digital Converter (ADC) to be extremely difficult. The design of RF amplifier also becomes increasingly difficult as the PAPR increases.

To mitigate the effect of such large PAPRs on performance degradation of the OFDM system, the design of the OFDM system needs to incorporate costly RF hardware, such as efficient and large linear dynamic range power amplifiers. Incorporating costly RF hardware, however, increases the cost of the OFDM system. There are basically three techniques that are used at present to reduce PAPR, they are Signal Distortion Techniques, Coding Techniques and finally the Scrambling Technique.

2.10.3 Co-channel Interference Mitigation in Cellular OFDM

A conventional OFDM system exhibits performance degradation due to frequency coherence of the channel. The closer the spacing between the adjacent subcarriers or the narrower the required coherence bandwidth is. In many channels, adjacent subcarriers will fall within the coherence bandwidth and will thereby experience flat fading.

In cellular communications systems, co-channel interference (CCI) is combated by combining adaptive antenna techniques, such as sectorization, directive antenna, antenna arrays, etc. Some are just avoidance techniques but others may be truly interference cancellation methodologies. Using OFDM in cellular systems will give rise to CCI. Similarly with the traditional techniques, with the aid of beam steering, it is possible to focus the receiver's antenna beam on the served user, while attenuating the co-channel interferers. This is significant since OFDM is sensitive to CCI.

2.11 Scalable OFDMA

2.11.1 Parameters and Principles

When designing OFDMA wireless systems the optimal choice of the number of subcarriers per channel bandwidth is a tradeoff between protection against multipath, Doppler shift, and design cost/complexity. Increasing the number of subcarriers leads to better immunity to the inter-symbol interference (ISI) caused by multipath (due to longer symbols); in turn, it increases the cost and complexity of the system (it leads to higher requirements for signal processing power and power amplifiers with the capability of handling higher peak-to-average power ratios). Having more subcarriers also results in narrower subcarrier spacing and therefore the system becomes more sensitive to Doppler shift and phase noise. Calculations

Table 2.3 SOFDMA parameters

System Parameters	Numerology			
Channel Bandwidth (MHz)	1.25	5	10	20
Sampling Frequency (MHz)	1.4	5.6	11.2	22.4
FFT Size (N_{FFT})	128	512	1,024	2,048
Number of used data subcarriers	72	360	720	1,440
Number of pilot subcarriers	12	60	120	240
Number of null guard band subcarriers	44	92	184	368
Number of Subchannels	2	8	16	32
Subcarrier frequency spacing	10.94 kHz			
Useful symbol time ($T_b = 1/f$)	91.4			
Guard time ($T_g = T_b/8$)	11.4			
OFDMA symbol duration ($T_s = T_b + T_g$)	102.9			
Number of OFDMA symbols in 5 ms	48			

show that the optimum tradeoff for mobile systems is achieved when subcarrier spacing is about 11 kHz [28].

Unlike many other OFDM-based systems such as IEEE 802.11a/g WLANs, the 802.16 standard supports variable bandwidth sizes for NLoS operations. In order to keep optimal subcarrier spacing, the FFT size should scale with the bandwidth. This concept is introduced in Scalable OFDMA (SOFDMA) [23, 28]. The concept of scalability was introduced to the IEEE 802.16 WirelessMAN OFDMA mode by the 802.16 Task Group *e* (TGe). A scalable physical layer enables standard-based solutions to deliver optimum performance in channel bandwidths, ranging from 1.25 MHz to 20 MHz with fixed subcarrier spacing for both fixed and portable/mobile usage models, while keeping the product cost low. Possible SOFDMA profiles are shown in Table 2.3.

In order to reduce system complexity and facilitate interoperability the decision was taken to limit the number of profiles for WiMAX. Currently, only two FFT sizes, 512 and 1024, are recommended in WiMAX. Besides the fixed (optimal) subcarrier spacing SOFDMA specifies that the number of subcarriers per subchannel should be independent of bandwidth, too. This results in the property that establishes the number of subchannels scales with FFT/bandwidth.

The basic principles of SOFDMA are the following:

- Subcarrier spacing is independent of bandwidth
- The number of subcarriers scales with bandwidth
- The smallest unit of bandwidth allocation, based on the concept of subchannels, is fixed and independent of bandwidth and other modes of operation
- The number of subchannels scales with bandwidth and the capacity of each individual subchannel remains constant

In addition to variable FFT sizes, the specification supports other features such as Advanced Modulation and Coding (AMC) subchannels, Hybrid Automatic Repeat Request (H-ARQ), high-efficiency uplink subchannel structures, Multiple-Input-Multiple- Output (MIMO) diversity and coverage enhancing safety channels, as well as other OFDMA default features, such as different subcarrier allocations and diversity schemes.

The SOFDMA modulation schemes make IEEE 802.16e system backward compatible to the FBWA IEEE 802.16-2004 specification, which simplifies “interoperability” because it would require user equipment for roaming between fixed and mobile BWA systems based on the IEEE 802.16 family of standards.

2.11.2 Reference Model

The Reference model for IEEE 802.16 is shown in the Fig. 2.13. IEEE 802.16 standard describes both the MAC and PHY for fixed and the mobile broadband wireless access. The major components of the reference model are Data/Control plane, management plane and the network management plane. The functions of each plane are defined in Table 2.4.

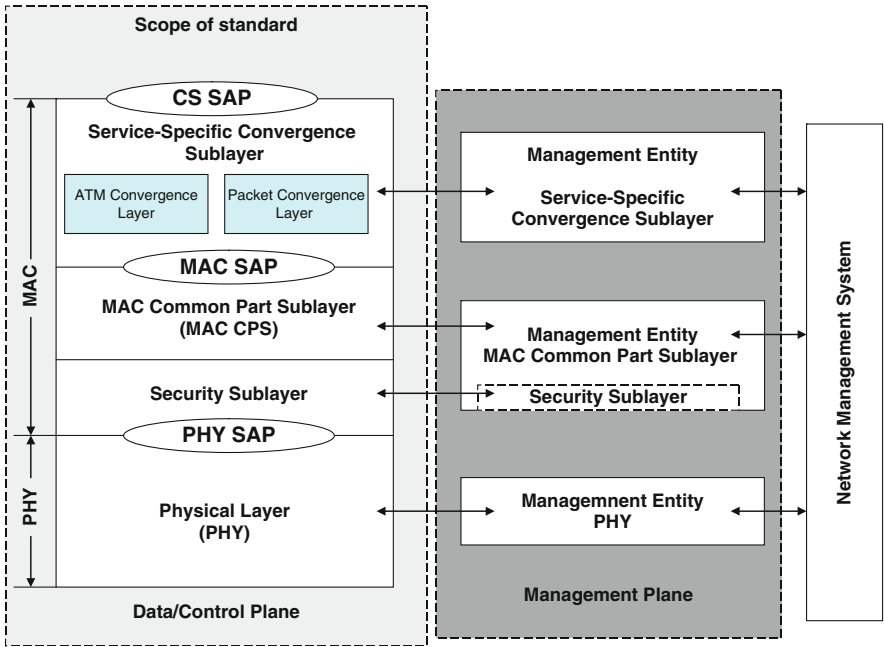


Fig. 2.13 IEEE 802.16 reference model (adapted from [19])

Table 2.4 IEEE 802.16 Planes and their functions	
Various IEEE 802.16 Planes	Functions
Control Plane	Short term control actions such as admission control, resource control, congestion control and load balanced routing
Management Plane	Long term management actions such as network provisioning, traffic engineering, monitoring
Data Plane	Operations on data to allow the transport of information

2.12 IEEE 802.16 PHY Layer

2.12.1 *Supported Frequency Bands*

The IEEE 802.16 standard supports multiple physical layer specifications. The first version of the standard only supported single carrier modulation in 10–66 GHz range of (licensed) spectrum. With the addition of OFDM and scalable OFDMA to the PHY layers, IEEE 802.16 now operates in NLoS environment and also provides mobility. Thus the scope of the IEEE 802.16 has been extended for use in below 11 GHz frequency bands along with the initially supported 10–66 GHz bands.

The range of frequencies supported in the licensed as well as unlicensed bands for IEEE 802.16 is as described below:

10–66 GHz licensed band – IEEE 802.16-2004 defines the PHY layer for the 10–66 GHz licensed spectrum. This frequency bands require LoS operation and the effect of multipath is negligible. The channel size within these bands is typically wide, between 25 and 28 MHz.

2–11 GHz licensed and licensed exempt – In this frequency bands, both licensed and licensed exempt bands are addressed. Additional physical functionality supports have been introduced to operate in LOS and NLOS environment and to mitigate the effect of multipath propagation. In fact, many of the IEEE 802.16 PHY's most advantageous capabilities are found in this frequency range. Operation in licensed exempt band experiences additional interference and coexistence issue. The PHY and MAC address mechanism like dynamic frequency selection (DFS) to detect and avoid interference for licensed exempt band. Although service provision in this frequency band is highly depends on design goals, vendors typically cite target aggregate data rates of up to 70 Mb/s in a 14 MHz channel.

2.12.2 *Channel Bandwidth*

IEEE 802.16 supports flexible channel bandwidth in integer multiple of 1.25 MHz, 1.5 MHz, 1.75 MHz, 2 MHz and 2.75 MHz with a maximum of 20 MHz. However, to ensure interoperability between different vendors' products, WiMAX forum has initially narrowed down the large choice of possible bandwidth to a few possibilities [19, 32].

2.12.3 *IEEE 802.16 PHY Interface Variants*

The standard has assigned a unique name to each physical interface. They have been described below along with their supported features in brief with the tabular representation in Table 2.5.

Table 2.5 IEEE 802.16 air interface nomenclature and description (Source: [11])

Designation	Band of Operation	Duplexing Mode	Notes
WirelessMAN-SC	10–66 GHz	TDD, FDD	Single Carrier
WirelessMAN-SCa	2–11 GHz Licensed band	TDD, FDD	Single Carrier technique for NLOS
WirelessMAN OFDM	2–11 GHz Licensed band	TDD	OFDM for NLOS operation
WirelessMAN OFDMA	2–11 GHz Licensed band	FDD	OFDM Broken into subgroups to provide multiple access in a single frequency band
WirelessHUMAN	2–11 GHz Licensed Band Exempt	TDD	May be SC, OFDM, OFDMA. Must include Dynamic Frequency Selection to mitigate interference

The PHY layer (or simply PHY) of IEEE 802.16 supports five different modes, as follows:

WirelessMAN-SC PHY – WirelessMAN-SC PHY specification is intended for operation in the 10–66 GHz frequency band. At these frequencies, LoS operation is practical necessity due to propagation characteristics. WirelessMAN-SC PHY does not support mobility. This is an adaptive-modulation (QPSK, 16-QAM and 64-QAM) scheme on a single carrier. Both TDD and FDD configurations are supported in order to allow operation in worldwide spectrum allocations [29]. Bandwidth allocation is based on a combination of TDMA and demand assigned multiple access (DAMA).

WirelessMAN-SCa PHY – WirelessMAN-SCa (or SC2 as it is alternatively known) is also a single-carrier modulation, defined for the 2–11 GHz band. It is designed for NLoS channels and also uses adaptive modulation. This standard supports “spread BPSK”, BPSK, QPSK, 16-QAM, 64-QAM, and 256-QAM modulations. Both Time- and Frequency-Division Duplex modes are defined. For uplink TDMA is used while for downlink either TDM or TDMA is applied.

WirelessMAN-OFDM PHY – This is based on orthogonal frequency division multiplexing (OFDM) with a 256 point transform to support multiple SS in 2–11 GHz frequency band. Access is done by TDMA. The WiMAX Forum has adopted this PHY specification for BWA. Because of employing OFDM and other features like multiple forward error correction method, this is the most suitable candidate to provide fixed support in NLOS environment.

Wireless MAN-OFDMA PHY – This PHY specification uses Orthogonal Division Multiple Access (OFDMA) which is an extension of Orthogonal Frequency Division Modulation (OFDM) with at least a single support of specified multipoint transform (2048, 1024, 512 or 128) to provide combined fixed and Mobile BWA. Operation is limited to below 11 GHz licensed band [30]. In this specification, multiple access is provided by addressing a subset of the multiple carriers to individual receivers.

WirelessHUMAN – Wireless HUMAN (High-speed Inlicensed Metropolitan Area Network) specification is targeted for license exempt bands below 11 GHz.

For unlicensed frequency bands, in addition to huge spectrum allocation available for public network access nationwide, any of the air interfaces specified for 2–11 GHz can be used. This specification, however, supports only TDD for duplexing [1]. Unlicensed bands allow experimentation and innovation, attracting significant interest for both academia and industry (manufacturers and service providers). It is, however, subject to various rules and constraints, such as transmitter power (or effective isotropic radiated power) limits.

The details on the above PHY air interface specifications follows:

Payload – Payload refers to individual units of transmission content that are of interest to some entity at the receiver.

Burst – A burst contains payload data and is formed according to the rules specified by the burst profile associated with the burst. The existence of the burst is made known to the receiver through the contents of either the uplink or downlink maps. For the uplink, a burst is a complete unit of transmission that includes a leading preamble, encoded payload, and trailing termination sequence.

Burst Set – A burst set is a self-contained transmission entity consisting of a preamble, one or more concatenated bursts, and a trailing termination sequence. For the uplink, burst set is synonymous with burst.

Burst Frame – A burst frame contains all information included in a single transmission. The DL and UL sub-frames each hold a burst frame.

Burst Profiles – Burst profile contains information about various parameters such as modulation type, FEC, preamble type and guard times. Burst profile is a part of downlink as well as uplink frame.

MAC Frame – A MAC frame refers to the fixed bandwidth intervals reserved for data exchange. For TDD, a MAC frame consists of one downlink and one uplink sub-frame, delimited by the transmit transition gap (TTG). For FDD, the MAC frame corresponds to the maximum length of the downlink sub-frame. FDD uplink sub-frames operate concurrently with downlink sub-frames but on a separate (frequency) channel.

Downlink Channel Descriptor (DCD) – DCD describes the downlink PHY characteristics of a downlink channel. The DCD is type of medium access control management message and is broadcasted by the BS at periodic intervals. The DCD contains information regarding frame duration codes and downlink burst profiles.

Uplink Channel Descriptor (UCD) – UCD describes the downlink PHY characteristics of a uplink channel. UCD is also a type of medium access control management message and is broadcasted periodically by the BS.

Downlink Interval Usage Codes (DIUCs) – DIUC is an interval usage code specific to a downlink. An interval usage code identifies a particular burst profile that can be used by a downlink or uplink transmission interval. Thus DIUC is used to identify the burst profile of downlink allocations in DL MAPs.

Uplink Interval Usage Codes (UIUCs) – UIUC is an interval usage code specific to an uplink.

Downlink MAP (DL MAP) – DL-MAP is type MAC message that defines burst start times for both time division multiplex and time division multiple access (TDMA) for downlink allocations. These allocations are specified in PHY specific

DL MAP elements. The DL MAP also include information about DIUCs to identify the burst profile. DL_MAP is the only mechanism used in WirelessMAN-SC and WirelessMAN-SC-a PHYs to describe DL access while in WirelessMAN-OFDM and for WirelessMAN-OFDMA an additional format called downlink frame prefix (DLFP) is also used.

Uplink MAP (UL MAP) – UL MAP describes the UL TDMA allocations in which exact time offsets, along with the burst profiles with which the SSs will transmit data is specified. Similar to the DL MAP, UL MAP also include information about UIUCs to identify the burst profile. The UL contention slots also form part of the UL MAP.

2.13 WirelessMAN-SC PHY

2.13.1 Overview

WirelessMAN-SC PHY mode of IEEE 802.16-2004 supports operation in the 10–66 GHz frequency band. This PHY specification is designed with a high degree of flexibility in order to allow service providers the ability to optimize system deployments with respect to cell planning, cost, radio capabilities, services and capacity. Both TDD and FDD configurations are allowed for flexible spectrum usage. The FDD mode also supports full-duplex SSs as well as half duplex SSs.

Both cases use a burst transmission format, whose framing mechanism supports adaptive burst profiling in which transmission parameters, including the modulation and coding schemes, may be adjusted individually to each SS on a frame-by-frame basis. The FDD case supports full-duplex SSs as well as half duplex SSs, which do not transmit and receive simultaneously.

The 802.16 supports adaptive burst profiling in which transmission parameters, including the modulation and coding scheme may be adjusted to each SS on frame by frame basis. The bandwidth allocation, that is, the allocation for channel time is based on combination of time division multiple access (TDMA) and demand-assigned multiple access (DAMA). The uplink channel is divided into a number of time slots. These time slots are assigned on frame by frame basis by the BS MAC. The SS uses these time slots for registration, ranging, contention bandwidth requests and user traffic. The downlink channel is TDM, with the information for each SS multiplexed onto a single stream of data and received by all SSs within the same sector. To support half-duplex FDD SSs, provision is also made for a TDMA portion of the downlink.

The downlink PHY includes a Transmission Convergence sub-layer that inserts a pointer byte at the beginning of the payload to help the receiver identify the beginning of a MAC PDU. Data bits coming from the Transmission Convergence sub-layer are randomized, FEC encoded, and mapped to a QPSK, 16-QAM, or 64-QAM (optional) signal constellation.

The uplink PHY is based upon TDMA burst transmission. Each burst is designed to carry variable-length MAC PDUs. The transmitter randomizes the incoming data, FEC encodes it, and maps the coded bits to a QPSK, 16-QAM (optional), or 64-QAM (optional) constellation.

2.13.2 Duplexing Techniques and PHY Type Parameter Encodings

2.13.2.1 FDD Mode and FDD frame

For FDD operation the uplink and downlink channels are on separate frequencies. The capability of the downlink to be transmitted in bursts facilitates the use of different modulation types and allows the system to simultaneously support full-duplex SSs and half-duplex SSs. The downlink carrier may be continuous. Figure 2.14 shows the basics of the FDD operation.

Figure 2.15 presents the half duplex FDD frame while Fig. 2.16 shows the full duplex one.

2.13.2.2 TDD Mode and TDD frame

In the TDD operation, the uplink and downlink transmissions share the same frequency band but are separated in time. A TDD frame has a fixed duration and contains one downlink and one uplink sub-frame. The TDD framing is adaptive, that is, the link capacity allocated to the downlink versus uplink may vary. Figure 2.17 shows the TDD frame structure.

Using TDD enables efficient support of asymmetric traffic for easy support of IP-based traffic, channel reciprocity and advanced antenna systems. Hybrid-automatic repeat request (H-ARQ) provides added robustness with rapidly

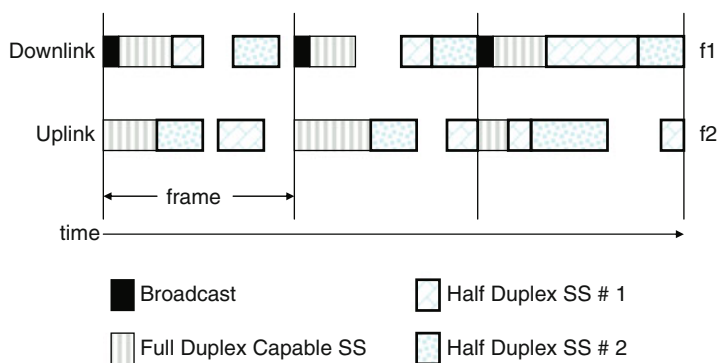


Fig. 2.14 FDD frame structure

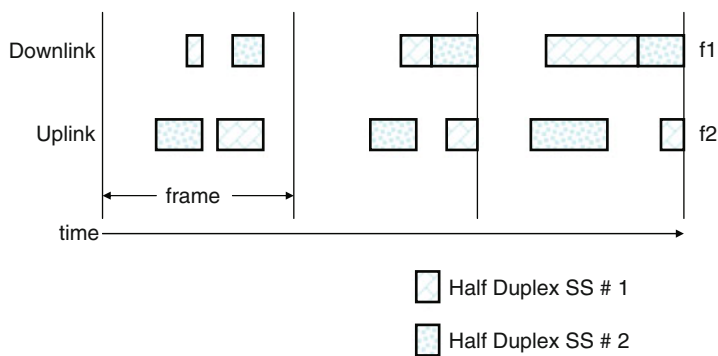


Fig. 2.15 H-FDD framing

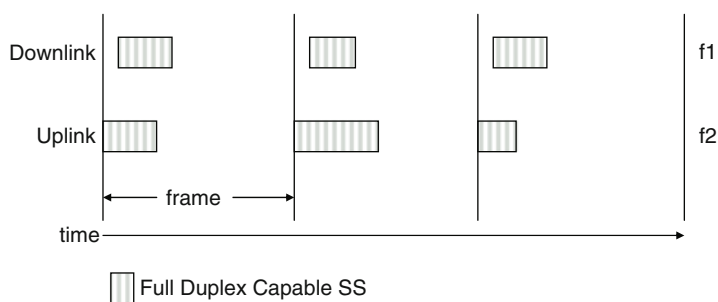


Fig. 2.16 Full Duplex framing

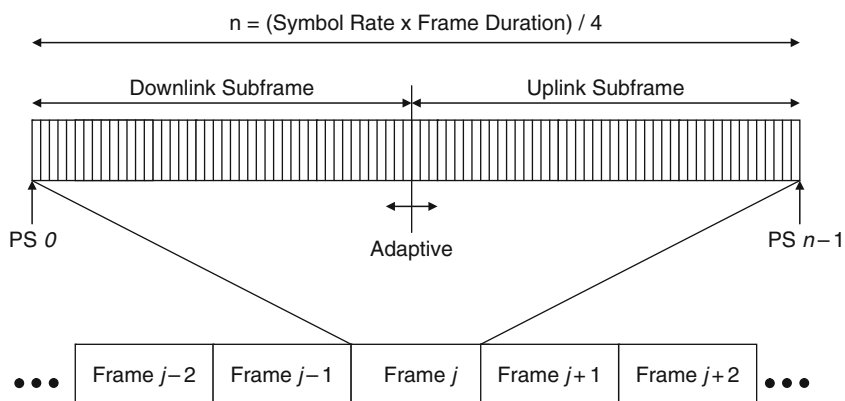


Fig. 2.17 TDD frame structure

changing radio path conditions in high mobility scenarios. TDD is less complex than FDD, where uplink and downlink traffic are separated by a guard time.

2.13.3 Frame Structure

The WirelessMAN-SC PHY operates in a framed format. Within each frame are a downlink sub-frame and an uplink sub-frame. The downlink sub-frame begins with information necessary for frame synchronization and control. In the TDD, the downlink sub-frame comes first, followed by the uplink sub-frame. The DL sub-frame begins with the information necessary for frame synchronisation and control as shown in Fig. 2.18. The downlink frame starts with a frame start preamble used by the PHY for synchronisation and equalization. This is followed by frame control section which is indicated in form of maps. Control section is followed by the TDM data section which is organized in the form of bursts. These burst profiles are organized in decreasing robustness fashion. The burst begins with the QPSK modulation followed by 16QAM and 64QAM. In the FDD case, uplink transmissions occur concurrently with the downlink frame. Supported frame durations allows for three frame durations 0.5, 1, and 2 ms.

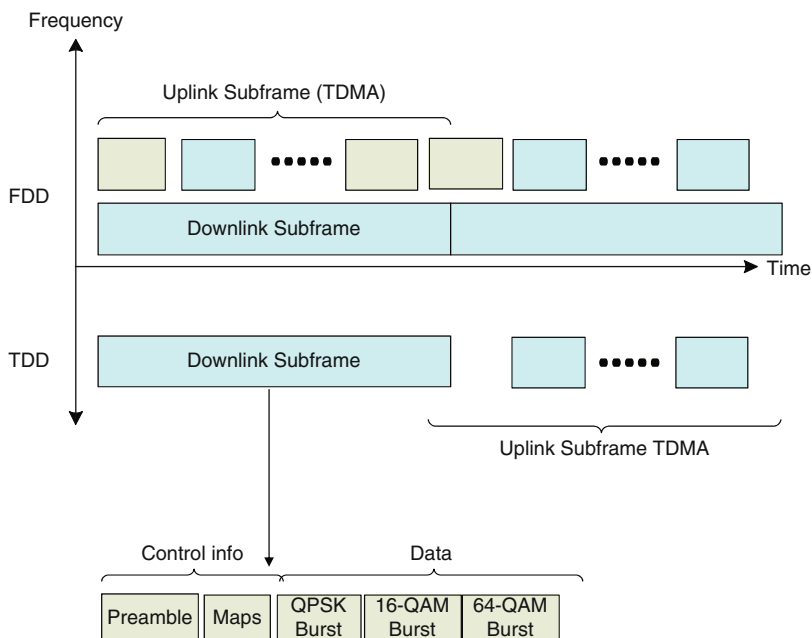


Fig. 2.18 Frame structure

2.13.4 Downlink PHY

In a TDD transmission, the BS basically transmits a TDM signal. This TDM signal is a series of individual subscriber stations allocated time slots. The downlink sub-frame starts with a preamble, which is used for synchronization and equalisation. The frame start preamble is a 32-symbol sequence generated by repeating a 16-symbol sequence. The frame control section is used to pass control information for the channel to all SSs, and this data is not encrypted.

The following section is a broadcasting control section that contains the DL-MAP and UL-MAP, which specified when physical layer transmissions (modulation and FEC changes) occur within the downlink frame as well as the UL-MAP. The TDM portions are just payloads to be transmitted to SSs which are organized into bursts with different burst profiles and therefore different level of transmission robustness. The bursts are always transmitted in order of decreasing robustness.

The DL-MAP portion of the frame control section provides listening SSs with the characteristics of the downlink channel. This information includes: PHY synchronization (i.e., schedule of physical layer transitions to include modulation and FEC changes), a downlink channel descriptor message (DCD), a programmable 48-bit BS identifier, and the number of data elements to follow. Reference [21] The DCD and the BS identifier identify the channel and the BS, respectively, and thus together are useful for situations where a SS is on the border of multiple IEEE 802.16 sectors or cells.

For example, with the use of a single FEC type with fixed parameters, data begins with QPSK modulation, followed by 16-QAM, followed by 64-QAM. In the case of TDD, a TTG separates the downlink sub-frame from the uplink sub-frame. The frames in TDMA portions may differ in bandwidth due to the dynamics of bandwidth demand for the variety of services that maybe active. Since the recipient SS is implicitly indicated in the MAC headers rather than in the DL-MAP, SSs listen to all portions of the downlink sub-frame they are capable of receiving. The structure of the downlink sub-frame using TDD is illustrated in Fig. 2.19.

The UL-MAP is used to communicate uplink channel access allocations to the SSs. Information provided in the UL-MAP include: Uplink channel identifier, uplink channel descriptor (UCD), number if information elements to map, allocation start time and map information elements. The UCD is used to provide SSs with information regarding the required uplink burst profile. The map information elements message identifies the SS this information applies to by using a connection identifier (CID). This message also provides an uplink interval usage code (UIUC) and offsets that are to be used by the SS to transmit on the uplink. The uplink interval usage code is used to specify the burst profile to be used by the SS on the uplink.

The transmit transition gap (TTG) is a gap between the downlink burst and the subsequent uplink burst. This gap allows time for the BS to switch from the transmitter to the receive mode while SSs switch from receive to transmit mode. During this gap, the BS and SS are not transmitting modulated data but simply

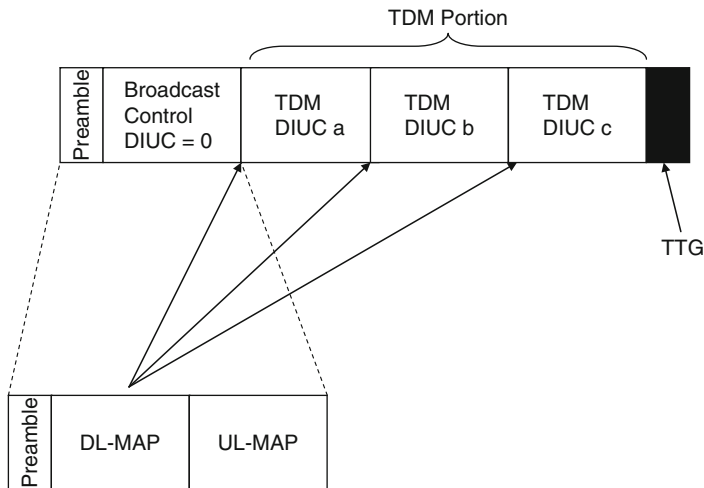


Fig. 2.19 TDD downlink sub-frame

allowing the BS transmitter carrier to ramp down, the transmit/receive (Tx/Rx) antenna switch to “actuate”, and the BS receiver section to “activate”. After the gap, the BS receiver shall look for the first symbols of uplink burst. This gap is an integer number of PS durations and starts on a PS boundary.

The receive transition gap (RTG) is a gap between the uplink burst and the subsequent downlink burst. This gap allows time, for the BS, to switch from receive to transmit mode and SSs to switch from transmit to receive mode. During this gap, the BS and SS are not transmitting modulated data but simply allowing the BS transmitter carrier to ramp up, the Tx/Rx antenna switch to “actuate”, and the SS receiver sections to “activate”. After the gap, the SS receivers shall look for the first symbols of QPSK modulated data in the downlink burst. This gap is an integer number of PS durations and starts on a PS boundary.

For FDD case, the structure of the downlink sub-frame is illustrated in Fig. 2.20. As in the TDD case, the downlink sub-frame begins with a Frame Start Preamble followed by a frame control section and a TDM portion organized into bursts transmitted in decreasing order of burst profile robustness. This TDM portion of the downlink sub-frame contains data transmitted to one or more of the following:

- Full-duplex SSs
- Half-duplex SSs scheduled to transmit later in the frame than they receive
- Half-duplex SSs not scheduled to transmit in this frame

The FDD downlink sub-frame continues with a TDMA portion used to transmit data to any half-duplex SSs scheduled to transmit earlier in the frame than they receive. This allows an individual SS to decode a specific portion of the downlink without the need to decode the entire downlink sub-frame. In the TDMA portion, each burst begins with the Downlink TDMA Burst Preamble for phase

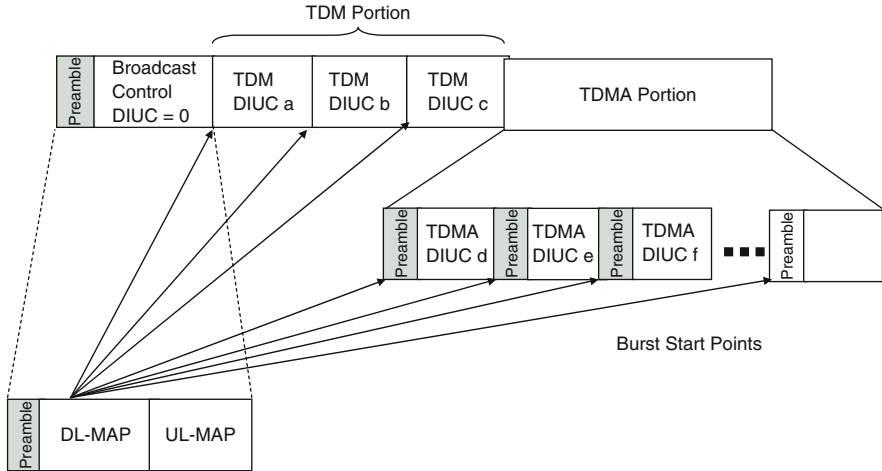


Fig. 2.20 FDD downlink sub-frame structure

resynchronization. Bursts in TDMA portion need not be ordered by burst profile robustness. The FDD frame control section includes a map of both the TDM and TDMA bursts.

The TDD downlink sub-frame, which inherently contains data transmitted to SSs, transmit later in the frame than they receive, and is identical in structure to the FDD downlink sub-frame for a frame in which no half duplex SSs are scheduled to transmit before they receive.

2.13.4.1 Downlink Channel Encodings

The downlink data sections are used for transmitting data and control messages to the specific SSs. The data are always FEC coded and are transmitted at the current operating modulation of the individual SS. In the TDM portion, data is transmitted in order of decreasing burst profile robustness.

For TDMA portion, the data are grouped into separately delineated bursts that need not be in robustness order. The DL-MAP message contains a map stating at which PS the burst profile changes occur.

The number of PSs allocated to a particular burst is calculated from the DL-MAP, which indicates the starting position of each burst as well as the burst profiles. If n denote the minimum number of PSs required for one FEC codeword of the given burst profile (where n is not necessarily an integer), then, $i = kn + j + q$, where k is the number of whole FEC code words that fit in the burst, j (not necessarily an integer) is the number of PSs occupied by the largest possible shortened codeword, and q ($0 \leq q < 1$) is the number of PSs occupied by pad bits inserted at the end of the burst to guarantee that i is an integer.

In Fixed Codeword Operation, j is always 0. A codeword can end partway through a modulation symbol as well as partway through a PS. When this occurs, the next codeword shall start immediately, with no pad bits inserted. At the end of the burst (i.e., when there is no next codeword), then $4q$ symbols are added as padding (if required) to complete the PS allocated in the DL-MAP. The number of padding bits in these padding symbols is $4q$ times the modulation density, where the modulation density is two for QPSK, four for 16-QAM, and six for 64-QAM. Note that padding bits may be required with or without shortening. Either k or j , but not both, may be zero. The number j implies some number of bits b . Assuming that j is nonzero, it shall be large enough such that b is larger than the number of FEC bits, r , added by the FEC scheme for the burst. The number of bits preferably an integral number of bytes) available for user data in the shortened FEC codeword is $b-r$. Any bits that may be left over from a fractional byte are encoded as binary 1 to ensure compatibility with the choice of 0xFF for pad. A codeword cannot have less than six information bytes. This is illustrated in Fig. 2.21.

In the case of TDMA downlink, a burst includes the Downlink TDMA Burst Preamble of length p PSs, and the DL-MAP entry points to its beginning, Fig. 2.22.

2.13.4.2 Downlink Transmission Convergence Sub-layer

The downlink payload is segmented into blocks of data designed to fit into the proper codeword size after the CS pointer byte is added. The payload length may vary,

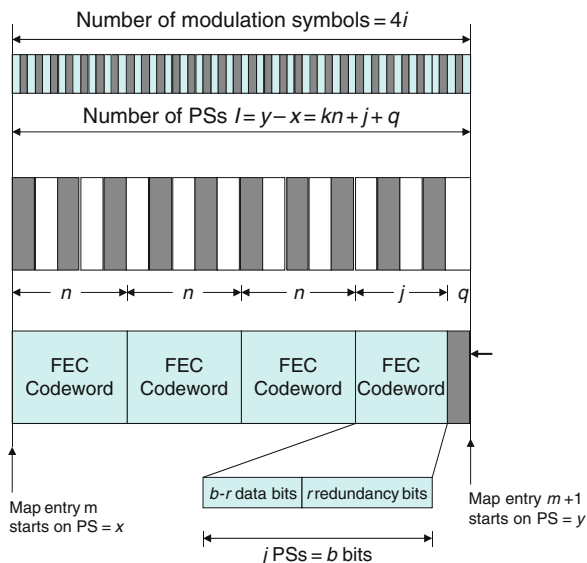


Fig. 2.21 DL-MAP usage with shortened FEC blocks –TDM case

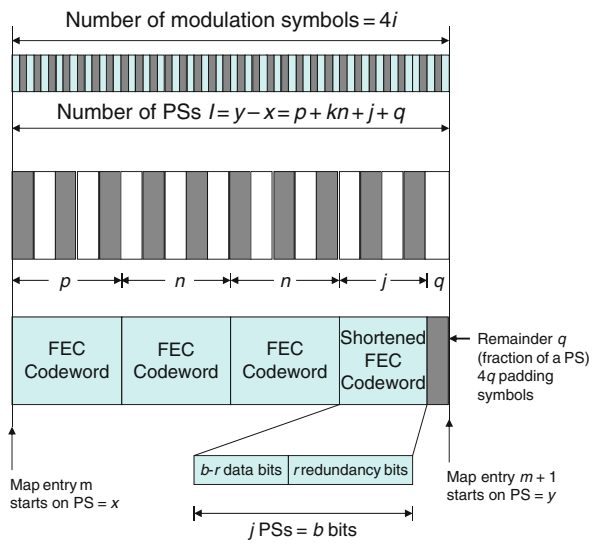


Fig. 2.22 DL-MAP usage with shortened FEC blocks –TDMA case

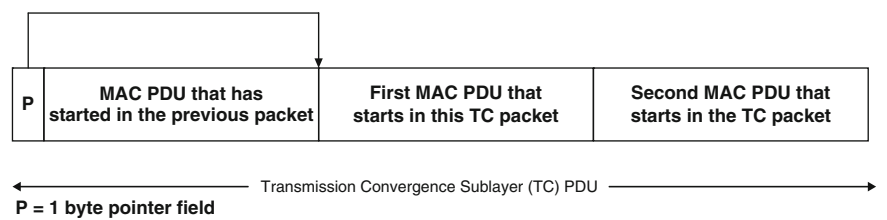


Fig. 2.23 Format of the downlink convergence sub-layer PDU

depending on whether shortening of code words is allowed or not for this burst profile. A pointer byte shall be added to each payload segment, as illustrated in Fig. 2.23.

The pointer field identifies the byte number in the packet. It indicates either the beginning of the first MAC PDU starts in the packet or the beginning of any stuff bytes that precede the next MAC PDU. For reference, the first byte in the packet is referred to as byte number 1. If no MAC PDU or stuff bytes begin in the CS packet then the pointer byte is set to 0. When no data is available to transmit, a stuff_byte pattern having a value (0xFF) shall be used within the payload, to fill any gaps between the IEEE 802.16 MAC PDUs. This value is chosen as an unused value for the first byte of the IEEE 802.16 MAC PDU, which is designed to never have this value (Fig. 2.23).

The downlink PHY coding and modulation for this mode is summarized in the block diagram from Fig. 2.24.

The downlink channel supports adaptive burst profiling on the user data portion of the frame. Up to twelve burst profiles can be defined. Since there are optional

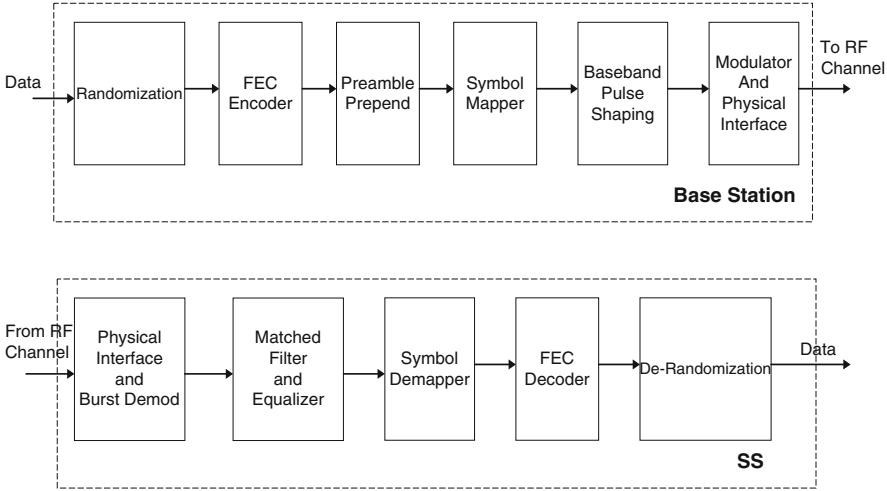


Fig. 2.24 Conceptual diagram of the downlink PHY sub-layer

Table 2.6 Selectable FEC code types (From [19])

Code types	Outer code	Inner code
1	Reed-Solomon over Galois field (GF) (256)	None
2	Reed-Solomon over GF (256)	(24,16) Block convolutional code
3 (Optional)	Reed-Solomon over GF (256)	(9,8) Parity check code
4 (Optional)	BTC	–

modulation and FEC schemes that can be implemented at the SS, a method for identifying the capability of the BS is required. Randomization is employed to minimize the possibility of transmission of an unmodulated carrier while ensuring adequate numbers of bit transitions to support clock recovery. The stream of downlink packets is randomized by modulo-2 addition of the data with the output of the Pseudo-Random Binary Sequence (PRBS) generator. Selected FEC Code types are presented in Table 2.6.

2.13.4.3 Downlink Modulation

The PHY uses a multilevel modulation scheme to maximize the utilization of the air-link. The modulation constellation can be selected per subscriber based on the quality of the RF channel. In the downlink, the BS supports QPSK and 16-QAM modulation and, optionally, 64-QAM. In changing from one burst profile to another, the BS uses one of two power adjustment rules: maintaining constant constellation peak power (power adjustment rule = 0), or maintaining constant constellation mean power (power adjustment rule = 1). In the former case, corner

points are transmitted at equal power levels regardless of modulation type, while in the latter the signal is transmitted at equal mean power levels regardless of modulation type. I and Q signals are filtered by square-root raised cosine filters prior to modulation. The excess bandwidth factor is $\alpha = 0.25$.

2.13.5 Uplink PHY

2.13.5.1 Uplink Sub-frame

The uplink Transmission Convergence sub-layer operation is identical to that of downlink. The structure of the uplink sub-frame used by the SS to transmit to the BS is shown in Fig. 2.25.

During the uplink sub-frame, three types of bursts may be transmitted by the SS depending upon the need aroused:

- Bursts that are transmitted in contention opportunities reserved for Initial Ranging
- Bursts that are transmitted in contention opportunities defined by Request Intervals reserved for response to multicast and broadcast polls
- Bursts that are transmitted in intervals defined by Data Grant IEs specifically allocated to individual SSs

Any of these bursts may be present in any uplink sub-frame and may occur in any order and quantity. The scheduler at BS indicates which bursts are present via the UL MAP message.

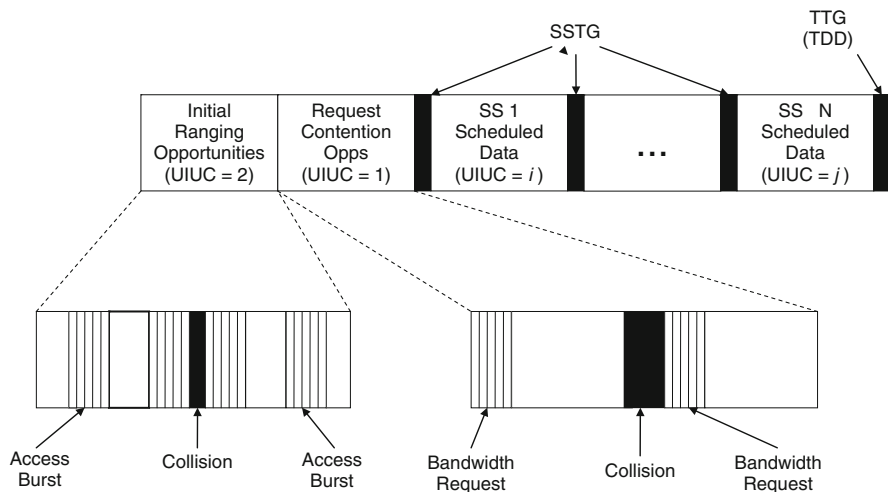


Fig. 2.25 Uplink sub-frame structure (From [19])

The bursts are separated by subscriber station transition gap (SSTGs), which separates transmission of the various SSs during the uplink sub-frame followed by a preamble allowing the BS to synchronize to the new SS.

Each uplink burst begins with an uplink preamble. This preamble is based upon a repetition of a $+45^\circ$ rotated Constant Amplitude Zero Auto-Correlation (CAZAC) sequence. Each Uplink Burst Profile in the Uplink Channel Descriptor (UCD) message includes the following parameters:

- Modulation type
- FEC Code Type
- Last codeword length
- Preamble Length
- Randomizer Seed

2.13.5.2 Uplink PHY Sub-layer

The uplink PHY coding and modulation are summarized in the block diagram shown in Fig. 2.26.

The uplink modulator implements a randomized, variable modulation which is set by the BS. QPSK is supported, while 16-QAM and 64-QAM are optional. In changing from one burst profile to another, the SS uses one of two power adjustment rules: maintaining constant constellation peak power (power adjustment rule = 0), or maintaining constant constellation mean power (power adjustment rule = 1). In the former case, corner points are transmitted at equal power levels regardless of modulation type, while, in the latter, the signal is transmitted at equal mean power levels regardless of modulation type.

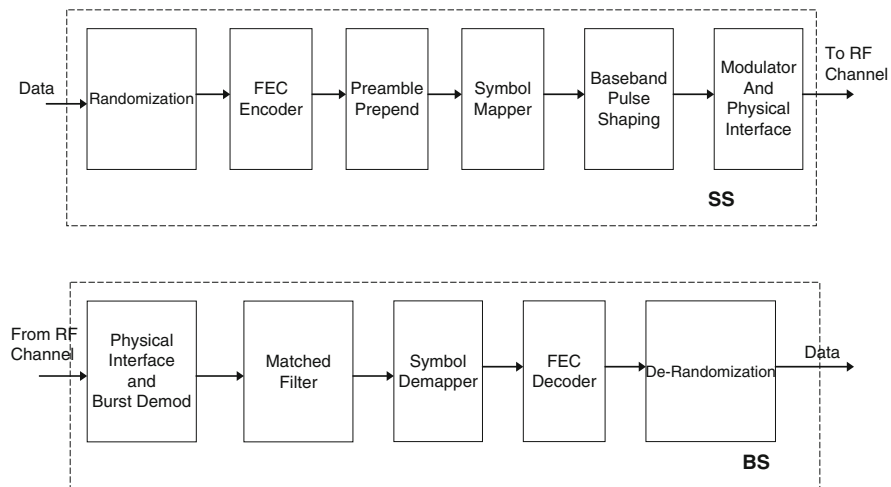


Fig. 2.26 Conceptual block diagram of the uplink PHY (From [19])

2.13.5.3 Channel Quality Measurements

Receive Signal Strength Indicator (RSSI) and Carrier-to-interference-plus-noise ratio (CINR) signal quality measurements and associated statistics can aid in such processes as BS selection/assignment and burst adaptive profile selection. As channel behaviour is time-variant, both mean and standard deviation are defined. The process by which RSSI measurements are taken does not necessarily require receiver demodulation lock; for this reason, RSSI measurements offer reasonably reliable channel strength assessments even at low signal levels. On the other hand, although CINR measurements require receiver lock, they provide information on the actual operating condition of the receiver, including interference and noise levels, and signal strength. When collection of RSSI measurements is mandated by the BS, an SS obtains an RSSI measurement from the downlink burst preambles. From a succession of RSSI measurements, the SS derives and updates estimates of the mean and the standard deviation of the RSSI. In the case of CINR, SS obtains CINR measurements.

2.14 WirelessMAN-OFDM PHY

The WirelessMAN-OFDM PHY is based on Orthogonal Frequency Division Multiplexing (OFDM) modulation and is designed for NLOS operation in the frequency bands below 11 GHz. It uses 256-point transform and access is by TDMA. This air interface is mandatory for license exempt bands.

2.14.1 Channel Coding

2.14.1.1 Types and Steps

Channel Coding is an important part of the communication system as it increases both the capacity and the coverage. In order to meet the BER requirements under moderate C/N conditions, channel coding is mandatory. There are two main types of coding schemes: block coding and convolutional coding. Block coding operates on finite length blocks and convolutional code works often in a continuous manner. A combination of these is proposed for the down link. Reed-Solomon forward error code is proposed as the outer code owing to its excellent distance properties and moderate implementation complexity. In the downlink, the inner code is inherent in the TCM modulation. There is no overhead in using TCM as it preserves the signal bandwidth. RS-code is optimal for correcting burst errors that might come from the TCM demodulator.

The uplink uses robust modulation and needs just a Reed-Solomon block code.

Channel coding involves three steps:

- Randomization
- Forward Error Correction (FEC)
- Interleaving

They are applied in this order at transmission. The inverse operations then performed, in the reverse order, at the receiver side (Fig. 2.27).

2.14.1.2 Randomization

Data randomization is performed independently on each burst for downlink and uplink data. Randomization is done to avoid long sequences of consecutive “ones” or consecutive “zeros”. If the amount of data to transmit does not fit exactly the amount of data allocated, padding of 0xFF (“1” only) is added to the end of the transmission block, for the unused integer bytes. The pseudorandom Binary Sequence (PBRs) generator used for randomisation is shown in Fig. 2.28. Except the preambles, each and every data byte to be transmitted enters sequentially into the randomiser, with the Most Significant Byte (MBS) first. Randomisation is not performed on preambles. Randomiser sequence is applied only to information bits.

The bits issued from the randomizer are then applied to the encoder. The randomizer is re-initialized on the downlink, at the start of each frame with the

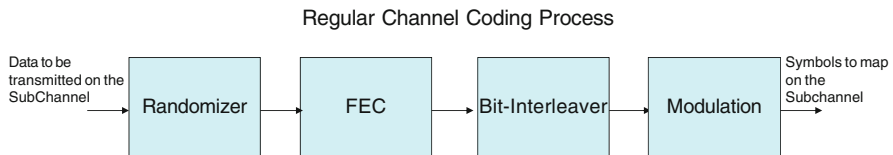


Fig. 2.27 OFDM PHY transmission chain

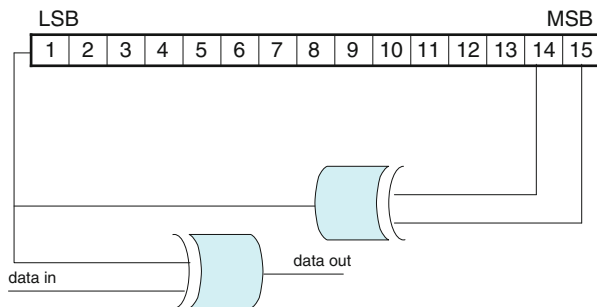


Fig. 2.28 PBRs generator used for the data randomization in OFDM and OFDMA PHY (From [19])

sequence: 1 0 0 1 0 1 0 1 0 0 0 0 0 0 0. The randomizer is not reset at the start of burst #1, but rather at start of subsequent bursts. The frame number used for initialization refers to the frame in which the downlink burst is transmitted.

2.14.1.3 FEC

FEC introduces redundancy in the data before it is transmitted. The redundant data (check symbols) are transmitted with the original data to the receiver. There are three methods of channel coding specified by OFDM PHY:

- Reed Solomon concatenated with convolutional coding(RS-CC)
- Block turbo codes(BTCs)
- Convolutional turbo codes(CTCs)

An FEC, consisting of the concatenation of a Reed-Solomon outer code and a rate-compatible convolutional inner code, is supported on both uplink and downlink. RS-CC is mandatory, whereas BTC and CTC are optional. More complex design issues are faced for BTC and CTC, although they are able to provide 2–3 dB higher gain.

2.14.2 Concatenated Reed–Solomon–Convolutional Code (RS-CC)

The Reed–Solomon encoding is derived from a systematic RS ($N = 255$, $K = 239$, $T = 8$) code using GF(28), where N is the number of overall bytes after encoding, K is the number of data bytes before encoding and T is the number of data bytes which can be corrected. This code is then shortened and punctured to enable variable block sizes and variable error-correction capability. The code after this is reduced to K' data bytes. Then, add $239-K'$ zero bytes as a prefix. After encoding discard these $239-K'$ zero bytes. When a codeword is punctured to permit T' bytes to be corrected, only the first $2T'$ of the total 16 parity bytes is employed.

Each RS block is encoded by the binary convolutional encoder, having a native rate of 1/2, and constraint length equal to 7. The encoding is performed by first passing the data in block format through the RS encoder and then passing it through a convolutional encoder. A single 0x00 tail byte is appended to the end of each burst. This tail byte is done after randomization. In the RS encoder, the redundant bits are sent before the input bits, keeping the 0x00 tail byte at the end of the allocation. When the total number of data bits in a burst is not an integer number of bytes, zero pad bits are added after the zero tail bits. The zero pad bits are not randomized.

Note that this situation can occur only in subchannelization. In this case, the RS encoding is not employed. Table 2.7 presents the block sizes and the code rates used

Table 2.7 Mandatory channel coding per modulation

Modulation	Uncoded block size (bytes)	Coded block size (bytes)	Overall coding rate	RS code	CC code rate
BPSK	12	24	1/2	(12,12,0)	1/2
QPSK	24	48	1/2	(32,24,4)	2/3
QPSK	36	48	3/4	(40,36,2)	5/6
16-QAM	48	96	1/2	(64,48,8)	2/3
16-QAM	72	96	3/4	(80,72,4)	5/6
64-QAM	96	144	2/3	(108,96,6)	3/4
64-QAM	108	144	3/4	(120,108,6)	5/6

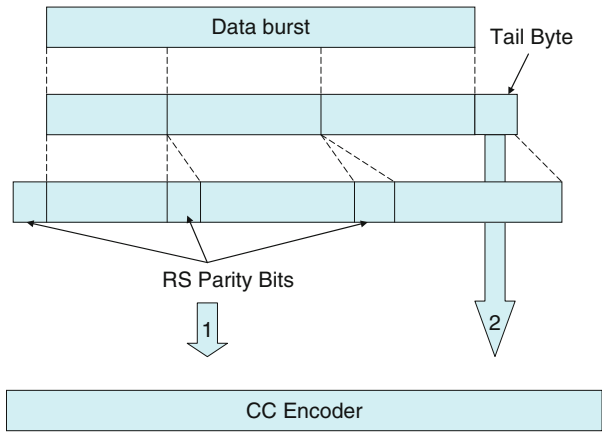


Fig. 2.29 RS-CC encoding process

for the different modulations and code rates. With 64-QAM (optional for license-exempt bands) the code is implemented if the modulation is implemented. In the case of BPSK modulation, the RS encoder is bypassed (Fig. 2.29).

2.14.2.1 Block Turbo Codes (BTCs)

Block Turbo Codes (BTC) are defined as an optional FEC for OFDM and OFDMA PHY. The BTC is also optional in WiMAX profiles.

In IEEE 802.16, both for OFDM and OFDMA PHY, the BTC is based on the product of two simple component codes, which are binary extended Hamming codes or parity check codes. It should be also noted that the codes are not the same for the two PHYs. Data bit ordering for the composite BTC matrix is defined such that the first bit in the first row is the LSB (Least Significant Byte) and the last data bit in the last data row is the MSB.

2.14.2.2 Interleaving

Interleaving is a technique where sequential data words or packets are spread across several transmitted data bursts. It is used to protect the transmission against long sequences of consecutive errors, which are very difficult to correct. These long sequences of error may affect a lot of bits in a row and can then cause many transmitted burst losses. All encoded data bits are interleaved by a block interleaver with a block size corresponding to the number of coded bits per the allocated subchannels per OFDM symbol, N_{chps} . The interleaver is defined by a two step permutation. The first ensures that adjacent coded bits are mapped onto nonadjacent subcarriers. The second permutation insures that adjacent coded bits are mapped alternately onto less or more significant bits of the constellation, thus avoiding long runs of lowly reliable bits.

After bit interleaving, the data bits are entered serially to the constellation mapper. BPSK, Gray-mapped QPSK, 16-QAM, and 64-QAM are supported, whereas the support of 64-QAM is optional for license-exempt bands. Pilot subcarriers are inserted into each data burst in order to constitute the Symbol and they are modulated according to their carrier location within the OFDM symbol.

2.14.2.3 Modulation

After bit interleaving, the data bits are entered serially to the constellation mapper. The OFDM PHY mandates BPSK as well as Gray-mapped QPSK, 16-QAM, and 64-QAM as shown in Figure 2.30. The 64-QAM constellation is optional for license-exempt bands. This is to allow use of IEEE 802.11 RF components as they do meet the 64-QAM performance requirements of IEEE 802.16 standard [29].

2.14.2.4 Pilot Modulation

Pilot subcarriers are modulated with a BPSK signal. The values to be used are derived by passing fixed initialization sequences through a PRBS generator with polynomial $X^{11} + X^9 + 1$ clocked with the OFDM symbol rate. This is done UL as well as DL separately. The value of the individual pilots in a single OFDM symbol are then defined as being either equal or the negative of the BPSK-modulated PRBS output.

2.14.2.5 Frame Structure

The OFDM PHY supports two different types of Frame Structures based on its two architectures, it supports, PMP and Mesh. The frame structure for PMP is mandatory but for mesh based architectures is optional. The frame durations for both architectures are between 2.5 and 20 ms.

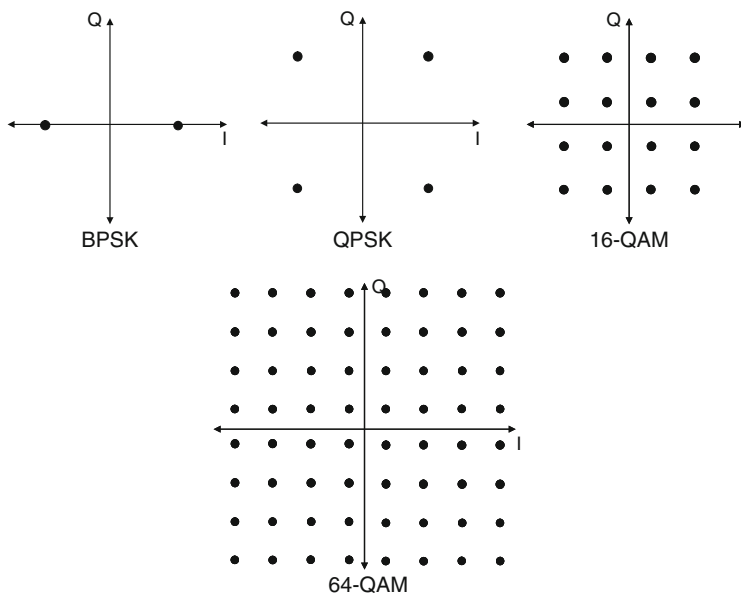


Fig. 2.30 BPSK, QPSK, 16-QAM, and 64 QAM constellations

2.14.2.6 Point-to-Multipoint

For point-to-Multipoint (PtM) architectures when licensed bands are used, the duplexing method is either FDD or TDD. FDD SSs is also supported for H-FDD. In license exempt bands, the duplexing method used is always TDD as it is provisioned to ensure better coexistence with the existing IEEE 802 standards.

The frame interval contains transmissions (PHY PDUs) of BS and SSs, gaps and guard intervals. The OFDM PHY also supports a frame-based transmission. A frame consists of a downlink sub-frame and an uplink sub-frame. A downlink sub-frame consists of only one downlink PHY PDU. An uplink sub-frame consists of contention intervals scheduled for initial ranging and bandwidth request purposes and one or multiple uplink PHY PDUs, each transmitted from a different SS.

A downlink PHY PDU starts with a long preamble, which is used for PHY synchronization. The preamble is followed by a FCH burst. The FCH burst is one OFDM symbol long and is transmitted using BPSK $\frac{1}{2}$ with the mandatory coding scheme. The FCH contains DL_Frame_Prefix to specify burst profile and length of one or several downlink bursts immediately following the FCH. A DL-MAP message, if transmitted in the current frame, shall be the first MAC PDU in the burst following the FCH. An UL-MAP message immediately follows either the DL-MAP message (if one is transmitted) or the DLFP. If UCD and DCD messages are transmitted in the frame, they immediately follow the DL-MAP and UL-MAP messages.

The FCH is followed by one or multiple downlink bursts, each transmitted with different burst profile. Each downlink burst consists of an integer number of OFDM

symbols. Location and profile of the first downlink burst is specified in the Downlink Frame Prefix (DLFP). The location and profile of the maximum possible number of subsequent bursts shall also be specified in the DLFP. At least one full DL-MAP must be broadcast in burst #1 within the Lost DL-MAP Interval. Location and profile of other bursts are specified in DL-MAP. Profile is specified either by a 4-bit Rate_ID (for the first DL burst) or by DIUC. The DIUC encoding is defined in the DCD messages. HCS field occupies the last byte of DLFP. If there are unused IEs in DLFP, the first unused IE must have all fields encoded as zeros.

The DL Sub-frame may optionally contain an STC zone in which all DL bursts are STC encoded. If an STC zone is present, the last used IE in the DLFP shall have DIUC = 0 and the IE shall contain information on the start time of the STC zone. The STC zone ends at the end of the frame. The STC zone starts from a preamble and an STC encoded FCH-STC burst, which is one symbol with the same payload format. The FCH-STC burst is transmitted at BPSK rate $\frac{1}{2}$. It is followed by one or several STC encoded PHY bursts. The first burst in the STC zone may contain a DL-MAP applicable only to the STC zone. If DL-MAP is present, it shall be the first MAC PDU in the payload of the burst.

With the OFDM PHY, a PHY burst, either a downlink PHY burst or an uplink PHY burst, consists of an integer number of OFDM symbols, carrying MAC messages, that is, MAC PDUs. To form an integer number of OFDM symbols, unused bytes in the burst payload may be padded by the bytes 0xFF. Then the payload should be randomized, encoded, and modulated using the burst PHY parameters specified by this standard. If an SS does not have any data to be transmitted in an UL allocation, the SS shall transmit an UL PHY burst containing a bandwidth request header, with BR = 0 and its basic CID. If the allocation is large enough, an AAS enabled SS may also provide an AAS Feedback Response (AAS-FBCK-RSP) message. An SS transmits during the entirety of all of its UL allocations, using the standard padding mechanism to fill allocations if necessary (Fig. 2.31).

In each TDD frame, the TTG and RTG is inserted between the downlink and uplink sub-frame and at the end of each frame, respectively, to allow the BS to turn around. In TDD and H-FDD systems, subscriber station allowances must be made by a transmit-receive turnaround gap SSTTG and by a receive-transmit turnaround gap SSRTG. The BS shall not transmit downlink information to a station later than (SSRTG+RTD) before its scheduled uplink allocation, and shall not transmit downlink information to it earlier than (SSTTG-RTD) after the end of scheduled uplink allocation, where RTD denotes Round-Trip Delay. The parameters SSRTG and SSTTG are capabilities provided by the SS to BS upon request during network entry (Fig. 2.32).

2.14.2.7 Mesh

The PMP topology supports both TDD and FDD duplexing modes, but for Mesh only TDD mode is supported. For Mesh mode there is no separate downlink and

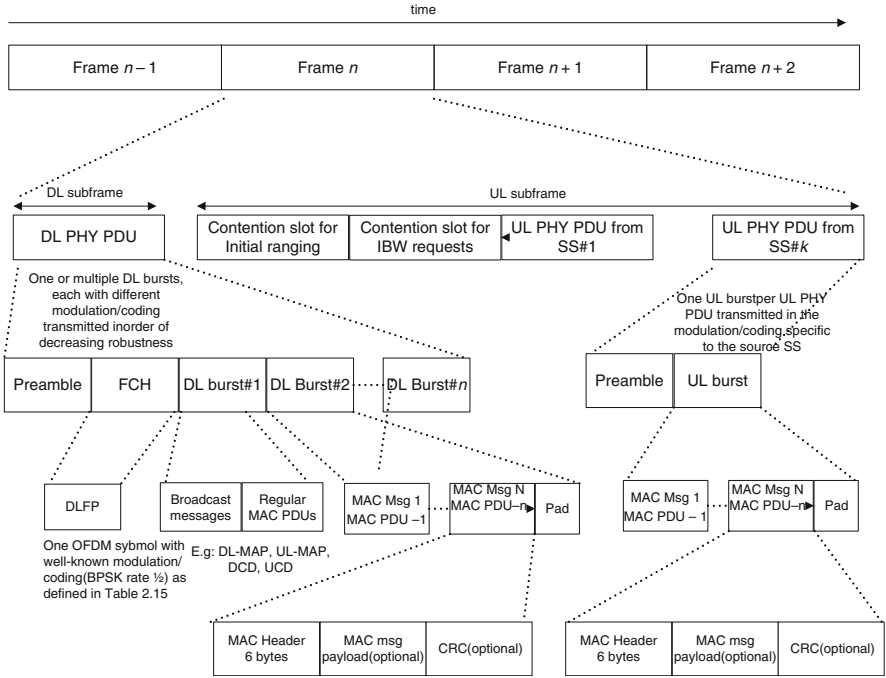


Fig. 2.31 Example of the OFDM structure with TDD (adapted from [19])

uplink sub-frames as all the stations have the same hierarchy. In addition to the PMP frame structure IEEE 802.16 defines, an optional frame structure to facilitate Mesh networks. The contents of the mesh frame are described below (Fig. 2.33).

A Mesh frame consists of a control and data sub-frame. The control sub-frame serves two basic functions. One is the creation and maintenance of cohesion between the different systems, termed “network control”. The other is the coordinated scheduling of data-transfers between systems, termed “schedule control” frames with a network control sub-frame occur periodically, as indicated in the Network Descriptor. All other frames have a schedule control sub-frame. The length of the control sub-frame is fixed and of length OFDM symbols, with indicated in the Network Descriptor.

2.14.2.8 Network Control Sub-frame

During a network control sub-frame, the first seven symbols are allocated for network entry, followed by sets of seven symbols for network configuration. During a schedule control sub-frame, the Network Descriptor indicates how many (MSH-DSCH-NUM) Distributed Scheduling messages may occur in the control sub-frame. The first symbols are allocated to transmission bursts containing

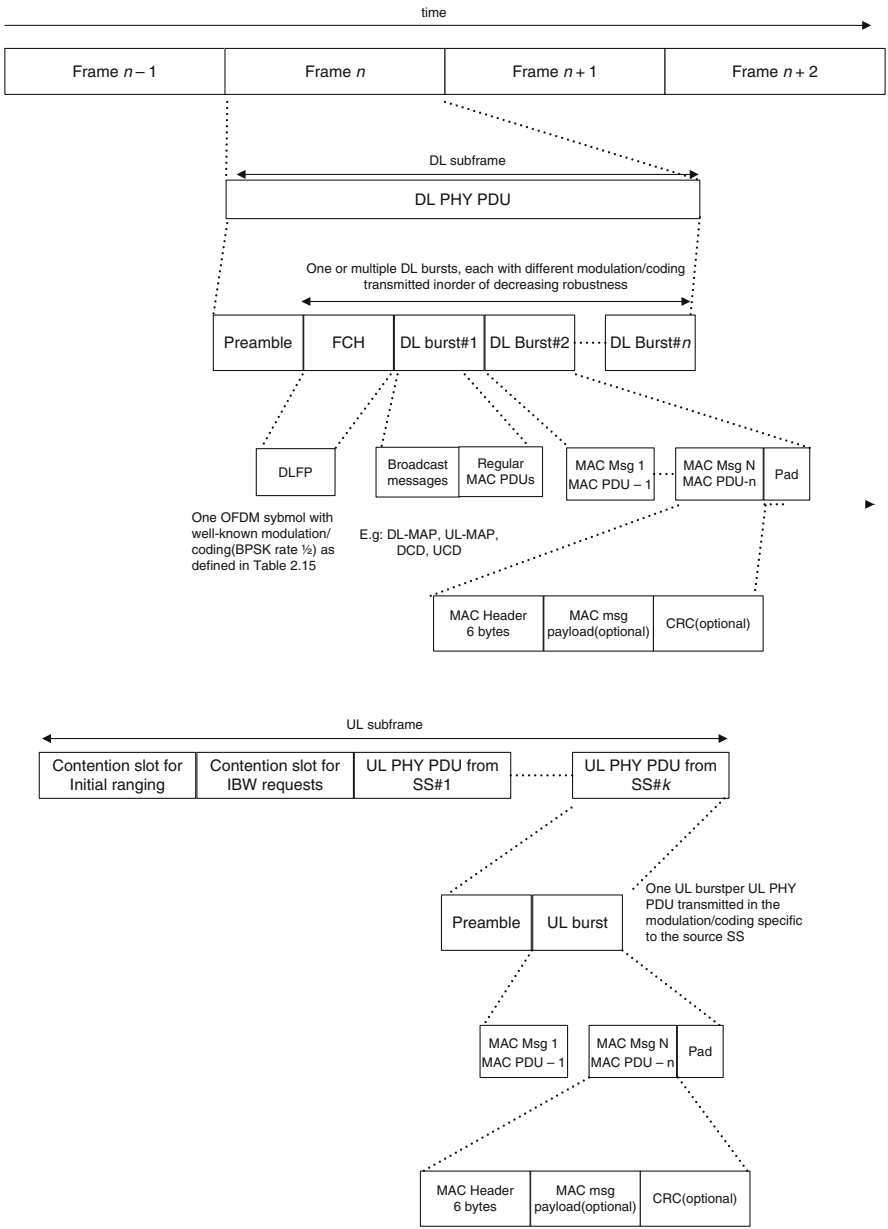


Fig. 2.32 OFDM frame structure with FDD (adapted from [19])

MSH-CSCH and MSH-CSCF PDUs, whereas the remainder is allocated to transmission bursts containing MSH-DSCH PDUs. Distributed Scheduling messages (using the long preamble) may further occur in the data sub-frame if not in conflict with the scheduling dictated in the control sub-frame.

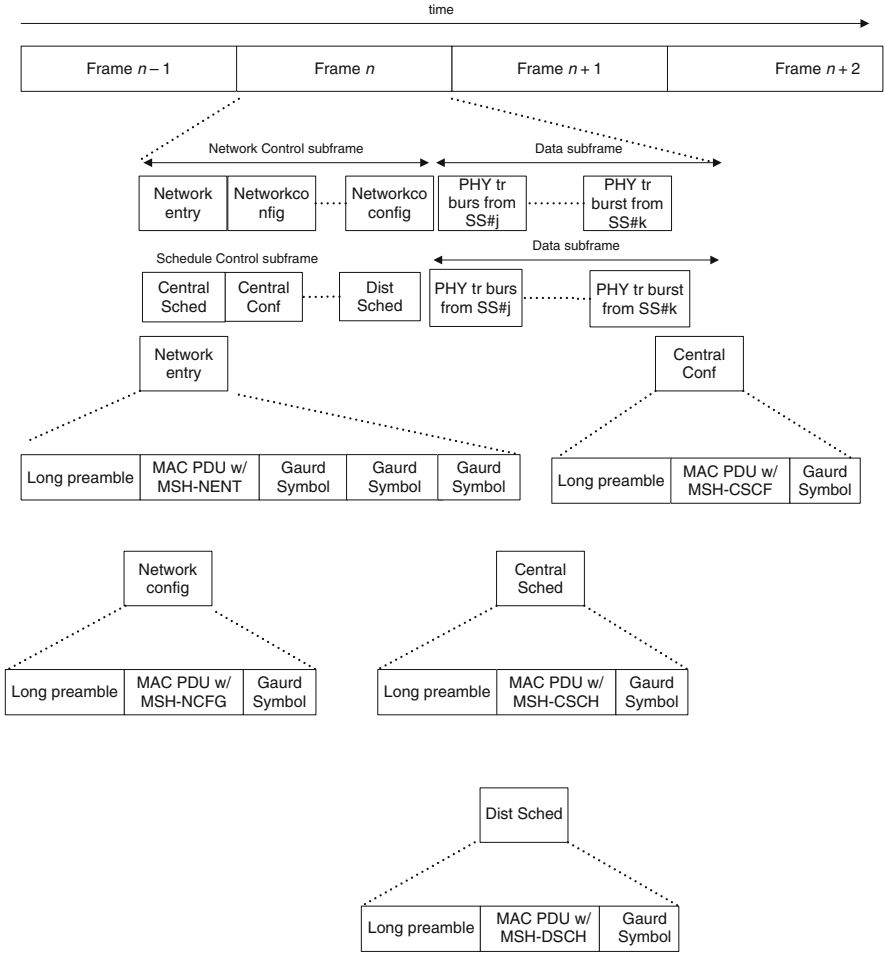


Fig. 2.33 Mesh frame structure (adapted from [19])

All transmissions in the control sub-frame are sent by using QPSK-1/2 with the mandatory coding scheme. The data sub-frame is divided into minislots, which are, with possible exception of the last minislot in the frame, of size ceiling $[(\text{OFDM symbols per frame} - \text{MSH-CTRL-LEN} \times 7)/256]$. A scheduled allocation consists of one or more minislots.

2.14.2.9 Control Mechanism: Synchronization

For TDD and FDD realizations, it is recommended (but not required) that all BSs be time synchronized to a common timing signal. In the event of the loss

of the network timing signal, BSs may continue to operate and automatically resynchronize to the network timing signal when it is recovered. For both FDD and TDD realizations, frequency references derived from the timing reference may be used to control the frequency accuracy of Base-Stations provided that they meet the frequency accuracy requirements.

2.14.2.10 Control Mechanism: Ranging

As a part of control mechanism **Ranging** is the first process performed by BS to communicate with the SS. There are two types of ranging processes – initial ranging and periodic ranging.

Initial ranging, that is, coarse synchronization is done under two conditions: first to initiate registration (or re-registration) of an SS with a BS and, secondly, during transmission on a periodic basis.

Initial ranging uses the initial ranging contention-based interval, which requires a long preamble. The periodic ranging uses the regular uplink burst. During registration process, the new subscriber tries to register during the random access channel. If it is successful, then it is entered into a ranging process under control of the BS. The ranging process is cyclic in nature where default time and power parameters are used to initiate the process followed by cycles. These parameters are monitored, measured and stored at the BS, and transmitted to the subscriber unit for use during normal exchange of data. During normal exchange of data, the stored parameters are updated in a periodic manner based on configurable update intervals to ensure that changes in the channel can be accommodated. The update intervals shall vary in a controlled manner on a subscriber unit by subscriber unit basis.

Regardless of duplexing type, the appropriate duration of the Initial Ranging slot used for initial system access depends on the intended cell radius. It is mandatory that the initial ranging transmissions use a long preamble and the most robust mandatory burst profile. In case there is need of re-registration the same process of registration is followed.

The use of BW by SS to transmit the preamble depends upon whether it is long or subchannelized. The long preamble is transmitted on the entire BW while the subchannelized preamble is transmitted on 1/16 of the BW. But the long preamble and the subchannelized preamble is transmitted using the same total power. Therefore the spectral density of the long preamble is lower by a factor of 16 (about 12 dB) than the power spectral density of the subchannelized preamble.

The BS need only detect that energy is sent on a single subchannel and may respond by allocating a single subchannel identifying the SS by the Transmit Opportunity, Frame Number and ranging subchannel in which the transmission was received.

2.14.2.11 Control Mechanism: – Initial Ranging in AAS Systems

The above Initial Ranging process does not work if the BS is operating in the AAS mode. A BS supporting the AAS option therefore allocates AAS alert slot in the uplink sub-frame. This is the way AAS SSs that have to initially alert the BS of their presence.

2.14.2.12 Bandwidth Requesting

There may be two types of REQ Regions in a frame. These two types are REQ Region-Full and REQ Region-Focused. In a REQ Region-Full, when subchannelization is not active, each Transmit Opportunity consists of a short preamble and one OFDM symbol using the most robust mandatory burst profile. When subchannelization is active, the allocation is partitioned into Transmission Opportunities (TOs) both in frequency and in time. The width (in subchannels) and length (in OFDM symbols) of each TO is defined in the UCD message defining. The transmission of an SS contains a subchannelized preamble corresponding to the chosen, followed by data OFDM symbols using the most robust mandatory burst profile. In a REQ Region-Focused, a station sends a short code over a Transmit Opportunity that consists of four subcarriers by two OFDM symbols. Each Transmit Opportunity within a frame is indexed by consecutive Transmit Opportunity Indices. The first occurring Transmit Opportunity is indexed 0.

2.14.2.13 Power Control

As with frequency control, a power control algorithm is supported for the uplink channel with both an initial calibration and periodic adjustment procedure without loss of data. The objective of the power control algorithm is to bring the received power density from a given subscriber to a desired level. The received power density is defined as total power received from a given subscriber divided by the number of active subcarriers. When subchannelization is not employed, the number of active subcarriers is equal for all the subscribers and the power control algorithm brings the total received power from a given subscriber to the desired level. The base station should be capable of providing accurate power measurements of the received burst signal. When subchannelization is employed, the SS maintains the same transmitted power density unless the maximum power level is reached.

2.14.2.14 Channel Quality Measurements

Same as the above two PHY specifications, RSSI and CINR are used for signal quality measurement. Implementation of the RSSI and CINR statistics and their

reports is mandatory. Here, an SS obtains RSSI and CINR measurements from the OFDM downlink preambles, and reports them via REP-RSP messages.

2.15 WirelessMAN-OFDMA PHY

2.15.1 Overview

WirelessMAN-OFDMA is among the three specifications defined in IEEE 802.16 family for applications below 11 GHz. The IEEE 802.16e-2005 amendment was developed to extend the 802.16 Air Interface Standard to cover mobile applications. This amendment adopted OFDMA to provide the flexibility to deal with varied usage scenarios and the challenges associated with rapidly moving mobile users in a NLOS environment. IEEE 802.16e includes all the expansion of all three of the lower frequency PHY specifications.

This uses orthogonal frequency-division multiple access with a 2048-point transform and is designed for NLOS operation in the frequency bands below 11 GHz. For licensed bands, channel bandwidths allowed is limited to the regulatory provisioned bandwidth divided by any power of 2 no less than 1.0 MHz. In the OFDMA mode, the active subcarriers are divided into subsets of subcarriers; each subset is termed a subchannel. In the downlink, a subchannel may be intended for different (groups of) receivers; in the uplink, a transmitter may be assigned one or more subchannels, several transmitters may transmit simultaneously. The subcarriers forming one subchannel may, but need not to be adjacent. The concept is shown in Fig. 2.34.

An OFDMA symbol consists of a number of carriers equal to the size of the Fourier transform. The symbols are constructed from data, pilot, and null carriers:

Data carriers – for data transmission

Pilot carriers – the magnitude and phase of these carriers are known to the receiver and they are used for channel estimation

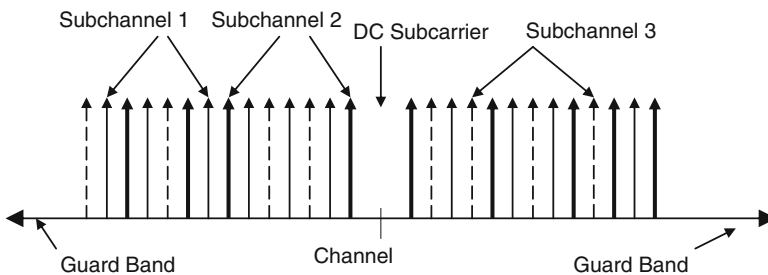


Fig. 2.34 OFDMA frequency description (three channel schematic example) [19]

Null carriers – there is no transmitted energy on these carriers to enable the signal to naturally decay and prevent leakage of energy into adjacent channels

The primitive parameters are the following (Table 2.8):

- BW : It is the nominal channel bandwidth.
- N_{used} : Number of used subcarriers (which includes the DC subcarrier).
- n : Sampling factor – In conjunction with BW and N_{used} , this parameter determines the subcarrier spacing, and the useful symbol time. This value is set to 8/7 as follows: for channel bandwidths that are a multiple of 1.75 MHz then $n = 8/7$ else for channel bandwidths that are a multiple of any of 1.25, 1.5, 2 or 2.75 MHz then $n = 28/25$ else for channel bandwidths not otherwise specified then $n = 8/7$.
- G : This is the ratio of CP time to “useful” time.

The 802.16e-2005 standard provides three subchannel allocation alternatives that can be selected based on the usage scenario as follows:

- Subcarriers can be scattered throughout the frequency channel range. This is referred to as fully used subchannelization or FUSC.
- Several scattered clusters of subcarriers can be used to form a subchannel. This is referred to as partially used subchannelization or PUSC.
- Subchannels can be composed of contiguous groups of subcarriers. This is referred to as adaptive modulation and coding or AMC.

Multiple OFDMA modulation modes are supported to accommodate variable channel bandwidths. This scalable architecture is achieved by using different FFT/IFFT sizes. Table 2.9 shows the relation between the supported channel bandwidths and the FFT size.

Table 2.8 Primitive parameters

Item	Value	Description
BW	1.25, 5, 10, 20	Bandwidth
N_{used}		# of used subcarriers
n	8/7, 28/25	Sampling factor
G	1/4, 1/8, 1/16, 1/32	Guard time ratio
N_{fft}	128, 512, 1024, 2048	FFT size
F_s	Floor($n \cdot BW / 8000$) * 8000	Sampling frequency
Δf	$F_s / N_{fft} = 11.16$ kHz	Frequency spacing
T_b	$1 / \Delta f = 89.6$ μ s	Useful symbol time

Table 2.9 FFT size and supported channel bandwidths

Channel bandwidths	FFT size
1.25	128
5	512
10	1024
20	2048

2.15.2 Subcarrier Allocation Modes

2.15.2.1 Adjacent Versus Distributed

An OFDMA symbol can be divided into several subchannels by grouping its subcarriers. WirelessMAN-OFDMA, in particular, allows two different grouping methods to realize the subchannelization: distributed and adjacent permutation. These grouping methods are shown in the Fig. 2.35, and their description is as follows:

Adjacent Permutation – In this type of permutation a subchannel is formed by grouping a block of contiguous data subcarriers. Adjacent Permutation is suitable for fixed, portable, or low mobility environments.

Distributed Permutation – Distributed permutation is implemented as Downlink Full Usage Sub-carriers (DL-FUSC), Downlink Partial Usage Sub-carriers (DL-PUSC), Uplink Partial Usage Subcarriers (UL-PUSC), Table 2.10. Subchannels are

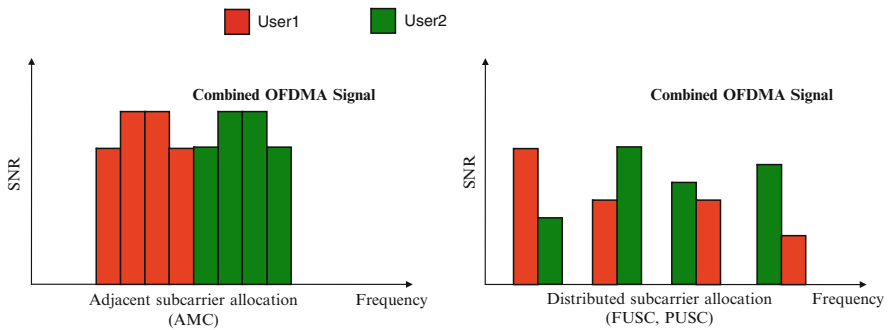


Fig. 2.35 Distributed and adjacent subcarrier allocation

Table 2.10 Comparison of adjacent and distributed subcarrier allocation schemes

Parameter	Adjacent subcarrier allocation (AMC)	Distributed subcarrier allocation (PUSC, FUSC)
Gain	Subchannelization gain and loading gain	Subchannelization gain and benefits of frequency diversity
Scheduling	Requires advanced scheduler that allocates subchannels according to channel characteristics	Simplified scheduler does not use info about the channel
Efficiency in multipath channel	Almost no data lost	Requires more redundancy (overhead) for forward error correction
Channel	Can be used in stationary channel	Can be used in fast-changing channel
AAS & MIMO	Easier implementation	More complicated implementation
Usage	Fixed, portable, nomadic, pedestrian speed	Mobile fast-moving subscribers

allocated with subcarriers in a pseudorandom way. The subcarriers for a described subchannel in a specific cell will be different from the subcarriers for that same subchannel in another cell. For example sub-carriers in subchannel 1 in cell 1 will be different than the subcarriers in the subchannel 1 in cell number 2. The pseudorandom calculation for the permutations gives an interference averaging by minimizing the bad effects of cell to cell interference.

2.15.2.2 OFDMA Frame

In IEEE 802.16e-2005 air interface, both FDD and TDD are supported. In case of FDD, the uplink and downlink sub-frames are transmitted simultaneously on different carrier frequencies while in the case of TDD, the uplink and downlink sub-frames are transmitted on the same carrier frequency at different times. Figure 2.36 shows the frame structure for TDD. For the FDD mode the frame structure is identical except that the UL and DL sub-frames are multiplexed on different carrier frequencies. For mobile stations, an additional duplexing mode, known as H-FDD (half-duplex FDD) is defined. H-FDD is a basic FDD duplexing scheme with the restriction that the MS cannot transmit and receive at the same time. From a cost and implementation perspective, an H-FDD MS is cheaper and

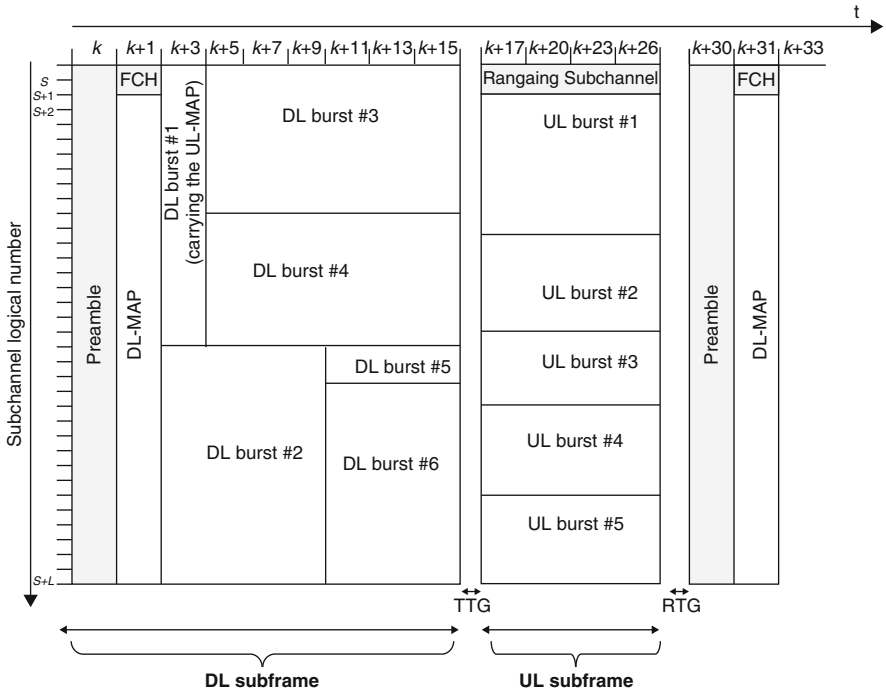


Fig. 2.36 Example of an OFDMA frame in TDD mode (adapted from [23])

less complex than its FDD counterpart, but the UL and DL peak data rate of, an H-FDD MS are less, owing to its inability to receive and transmit simultaneously.

An 802.16e TDD frame is built up by one downlink (DL) sub-frame and one uplink (UL) sub-frame. Each frame in the downlink transmission begins with a preamble followed by a DL transmission period and an UL transmission period. To separate the downlink frame from the uplink one, guard zones are inserted as shown in Fig. 2.36. In the case between the downlink and uplink frame the guard zone is Transmit Transition Gap (TTG) and between the end of the frame and the next frame the guard zone is Receive Transition Gap (RTG).

In TDD mode each DL sub-frame and UL sub-frame is divided into various zones, each using a different subcarrier permutation scheme. Some of the zones, such as DL PUSC, are mandatory; other zones, such as FUSC, AMC, UL PUSC, and TUSC, are optional. The relevant information about the starting position and the duration of the various zones being used in a UL and DL sub-frame is provided by control messages in the beginning of each DL sub-frame.

The other important sections of the TDD frame are the following:

- **Preamble:** The first OFDM symbol in the downlink sub-frame is used for transmitting the DL preamble. The preamble can be used for a variety of PHY layer procedures, such as time and frequency synchronization, initial channel estimation, and noise and interference estimation. The subcarriers in the preamble symbol are divided into a group of three carrier sets. The preamble, used for synchronization, is the first OFDM symbol of the frame.
- **Frame Control Header (FCH):** The FCH follows the preamble. The FCH is used for carrying system control information, such as the subcarriers used (in case of segmentation), the ranging subchannels, and the length of the DL-MAP message. This information is carried on the DL_Frame_Prefix message contained within the FCH. The FCH is always coded with the BPSK R1/2 mode to ensure maximum robustness and reliable performance, even at the cell edge. It provides the frame configuration information such as MAP message length and coding scheme and usable subchannels.
- **DL-MAP and UL-MAP:** The DL-MAP and UL-MAP provide subchannel allocation and other control information for the DL and UL sub-frames, respectively.
- **UL Ranging:** The UL ranging subchannel is allocated for mobile stations (MS) to perform closed-loop time, frequency, and power adjustment as well as bandwidth requests.

2.15.2.3 Multiple Subcarrier Allocation Zones

OFDMA PHY supports multiple subcarrier allocation zones (such as PUSC, FUSC, PUSC with all subchannels, optional FUSC, AMC, TUSC1, and TUSC2) within the same frame to enable the possibility of support for and coexistence of different types of SSs. Figure 2.37 shows the OFDMA frame with multiple zones.

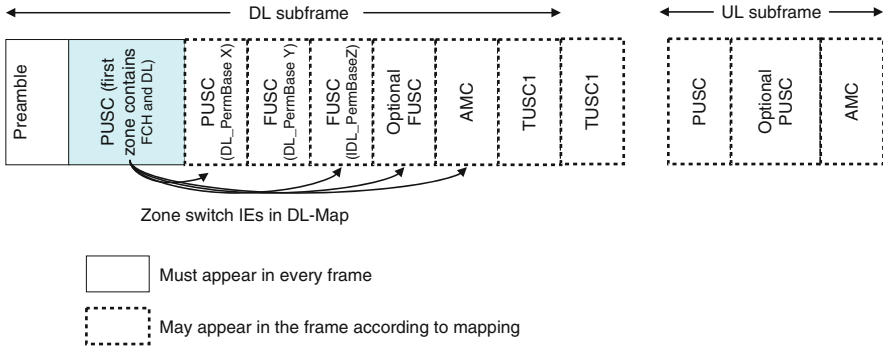


Fig. 2.37 Illustration of the OFDMA frame with multiple zones (adapted from [23])

The switching between zones is performed using an information element included in DL-MAP and UL-MAP. DL and UL sub-frames both start in PUSC mode where groups of subchannels are assigned to different segments by the use of dedicated FCH messages. The PUSC subcarrier allocation zone can be switched to a different type of subcarrier allocation zone through a directive from the PUSC DL-MAP. The PHY parameters such as channel state and interference levels may change from one zone to the next.

2.15.2.4 Time Frequency Mapping

In the OFDMA PHY, the mapping of data to physical subcarriers is performed in two steps. In the first step, data are mapped to one or more data slots on one or more logical subchannels. In the second step, for each data slot, each logical subchannel is then mapped to a number of physical subcarriers.

Logical mapping makes use of certain basic terms in its description described below.

1. **Slot** – Slot is the minimum possible data allocation in the time-frequency domain. It always consists of a single subchannel and two, three or six OFDM symbols depending on the physical mapping. Size of OFDMA slot depends on the OFDMA symbol structure, which varies for uplink and downlink, for FUSC and PUSC, and for the distributed subcarrier permutations and the adjacent subcarrier permutation.
 - For downlink FUSC using the distributed subcarrier permutation one slot is one subchannel by one OFDMA symbol.
 - For downlink PUSC using the distributed subcarrier permutation one slot is one subchannel by two OFDMA symbols.
 - For uplink PUSC using either of the distributed subcarrier permutations one slot is one subchannel by three OFDMA symbols.

- For uplink and downlink using the adjacent subcarrier permutation one slot is one subchannel by one OFDMA symbol.
2. **Segment** – A Segment is a subdivision of the set of available OFDMA subchannels that may include all available subchannels. One segment is used for deploying a single instance of the MAC. For example, a BS might segment the available subchannels among different sectors. There can be up to three segments where segment 0 must always contain subchannel group 0 and group1, Segment 1 may contain subchannel group 2 and segment 2 contains subchannel group 4.
 3. **Data Region** – In OFDMA, a Data Region is a two-dimensional allocation of a group of contiguous subchannels, in a group of contiguous OFDMA symbols. All the allocations refer to logical subchannels. A two dimensional allocation may be visualized as a rectangle, such as the 4×3 rectangle shown in Fig. 2.38. A data region can be transmitted in the downlink by the BS as a transmission to a SS or group of SSs. Figure 2.39 shows these concepts for 1024-FFT DL PUSC with three segments.
 4. **Subchannel Group** – Subchannel Group is set of contiguous subchannels. The allocations of subchannels to subchannel groups is fixed.
 5. **Perm Base** – It has been separately defined for DL and UL. In DL it is called DL PermBase which is an integer ranging from 0 to 31, which identifies the particular BS segment and is specified by MAC layer. It is set to preamble IDCell in the first zone and determined by the DL-MAP for other zones. For UL, there is a different integer called UL PermBase which ranges from 0 to 69 and is assigned by a management entity.
 6. **Permutation and Permutation Zone** – Permutation is mapping of logical subchannels to physical subcarriers. There are the following mechanisms for permutation:
 - PUSC (partial usage of subchannels)
 - FUSC (full usage of subchannels)

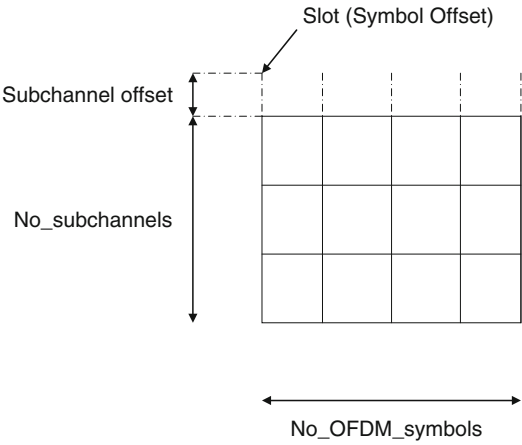


Fig. 2.38 Example of the data region which defines the OFDMA allocation

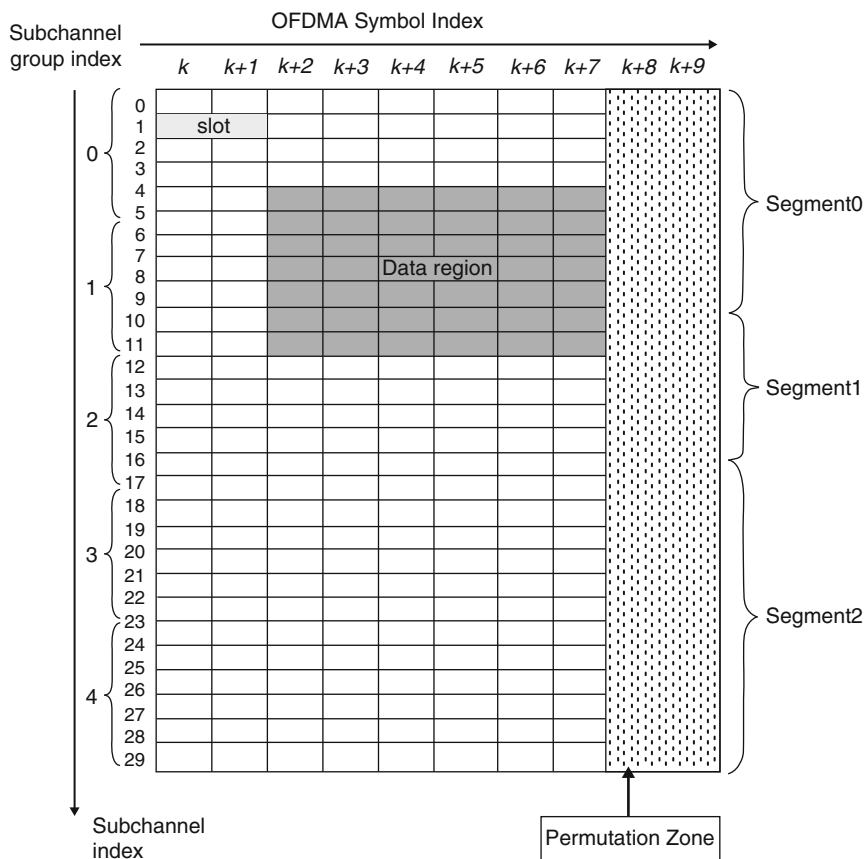


Fig. 2.39 Schematic indication of logical mapping elements

- Optional PUSC
- Optional FUSC
- AAS (Adaptive Antenna System)
- AMC (Adaptive Modulation and Coding)
- Option FUSC with all subchannels

Permutation Zone is a number of contiguous OFDMA symbols, in the DL or the UL, that use the same permutation formula. The permutation formula describes various configurations of pilot subcarriers, data subcarriers, subchannels, and slots.

The DL sub-frame or the UL sub-frame may contain more than one permutation zone.

Zones are used to help implement base station functionality such as beamforming, assigning subchannels to different sectors of a single cell, and to define subchannelization that reduces base station to base station interference.

2.15.2.5 Algorithms for OFDMA Data Mapping: Downlink

1. Segment the data after the modulation block into blocks sized to fit into one OFDMA slot.
2. Each slot should span one subchannels in the subchannel axis and one or more OFDMA symbols in the time axis. Map the slots such that the lowest numbered slot occupies the lowest numbered subchannel in the lowest numbered OFDMA symbol.
3. Continue the mapping such that the OFDMA subchannel index is increased. When the edge of the Data Region is reached, continue the mapping from the lowest numbered OFDMA subchannel in the next available symbol.

2.15.2.6 Algorithms for OFDMA Data Mapping: Uplink

The UL mapping consists of two steps. In the first step, the OFDMA slots allocated to each burst are selected. In the second step, the allocated slots are mapped. Details are as follows:

Step 1: Allocate OFDMA slots to bursts:

1. Segment the data into blocks sized to fit into one OFDMA slot.
2. Each slot shall span one or more subchannels in the subchannel axis and one or more OFDMA symbols in the time axis. Map the slots such that the lowest numbered slot occupies the lowest numbered subchannel in the lowest numbered OFDMA symbol.
3. Continue the mapping such that the OFDMA symbol index is increased. When the edge of the UL Zone is reached continue the mapping from the lowest numbered OFDMA symbol in the next available subchannel.
4. An UL allocation is created by selecting an integer number of contiguous slots, according to the ordering of steps 1–3. This results in the general Burst structure shown by the gray area in Fig. 2.40.

Step 2: Map OFDMA slots within the UL allocation:

1. Map the slots such that the lowest numbered slot occupies the lowest numbered subchannel in the lowest numbered OFDMA symbol.
2. Continue the mapping such that the Subchannel index is increased. When the last subchannel is reached, continue the mapping from the lowest numbered subchannel in the next OFDMA symbol that belongs to the UL allocation. The resulting order is shown by the arrows in Fig. 2.41.

2.15.2.7 Symbol Structure for PUSC

The symbol structure is formed by pilots, data, and zero subcarriers. The symbol is first divided into basic clusters and zero carriers are allocated. Pilots and data

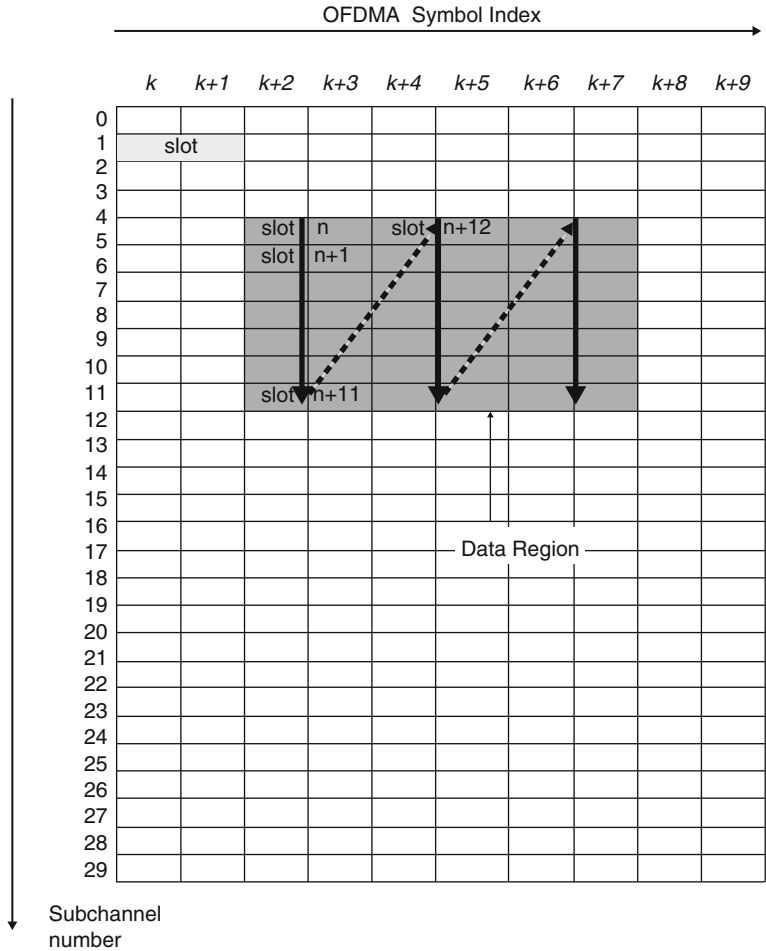


Fig. 2.40 Example of mapping OFDMA slots to subchannels and symbols in the downlink (in the PUSC mode)

carriers are allocated within each cluster. Pilot positions are marked separately for odd and even OFDM symbol. These subcarriers will be separated from the rest before permutation. For example, consider subcarriers of logical cluster ‘0’ (With Perm Base = 0, it is the sixth physical cluster). These subcarriers are numbered as 0–13. Their positions with respect to the absolute subcarrier index (0–2047) are 268–281. The pilot subcarriers for odd symbols will be ‘4’ and ‘8’ (‘272’ and ‘276’ with respect to absolute subcarrier index). For even OFDM symbols ‘0’ and ‘12’ (‘268’ and ‘280’) will be pilot positions. The rest 12 subcarriers will be used as data subcarriers (Fig. 2.42).

Table 2.11 shows the parameters for the symbol structure

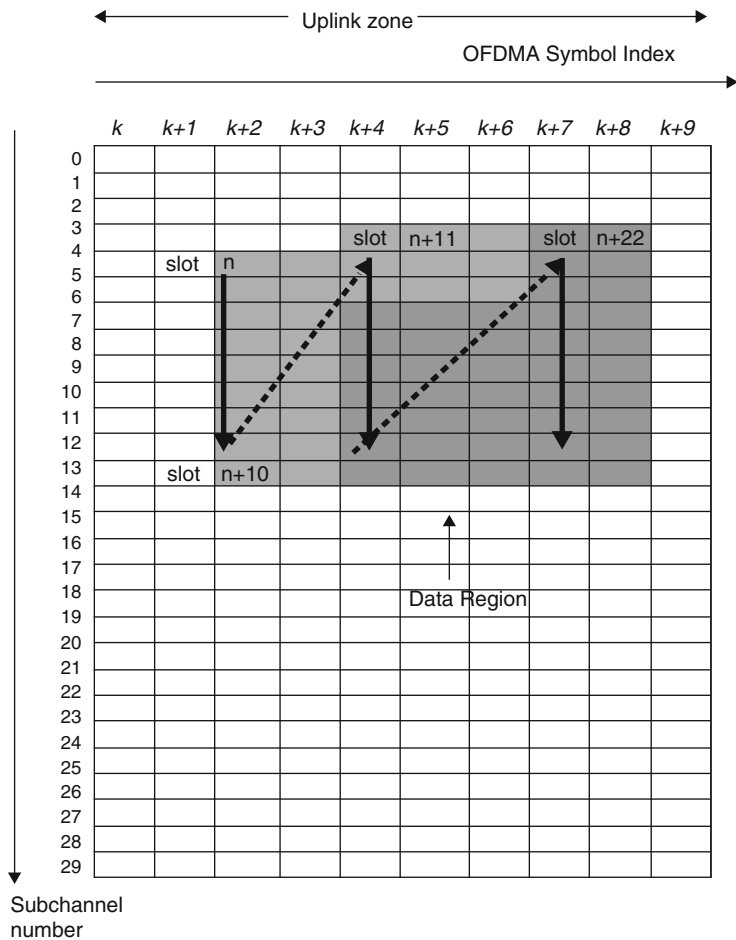


Fig. 2.41 Example of mapping OFDMA slots to subchannels and symbols in the uplink

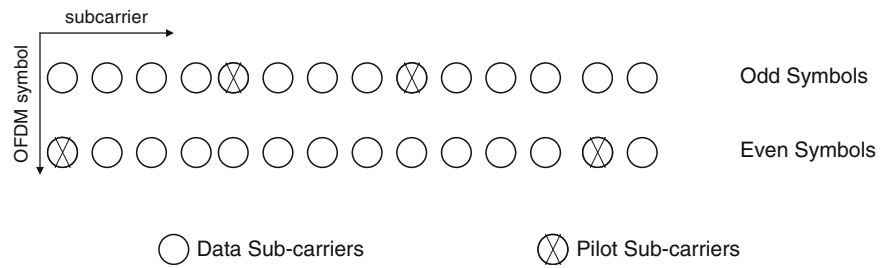


Fig. 2.42 DL PUSC cluster structure

Table 2.11 2048 FFT OFDMA downlink subcarrier allocations for PUSC

Parameter	Value	Comments
Number of DC subcarriers	1	Index 1024
Number of Guard subcarriers, Left	184	
Number of Guard subcarriers, Right	183	
Number of used subcarriers (Nused)	1,681	Number of all subcarriers used within a symbol, including all possible allocated pilots and the DC carrier
Number of subcarriers per cluster	14	
Number of clusters	120	
Renumbering sequence	1	Used to renumber clusters before allocation to subchannels: 6, 108, 37, 81, 31, 100, 42, 116, 32, 107, 30, 93, 54, 78, 10, 75, 50, 111, 58, 106, 23, 105, 16, 117, 39, 95, 7, 115, 25, 119, 53, 71, 22, 98, 28, 79, 17, 63, 27, 72, 29, 86, 5, 101, 49, 104, 9, 68, 1, 73, 36, 74, 43, 62, 20, 84, 52, 64, 34, 60, 66, 48, 97, 21, 91, 40, 102, 56, 92, 47, 90, 33, 114, 18, 70, 15, 110, 51, 118, 46, 83, 45, 76, 57, 99, 35, 67, 55, 85, 59, 113, 11, 82, 38, 88, 19, 77, 3, 87, 12, 89, 26, 65, 41, 109, 44, 69, 8, 61, 13, 96, 14, 103, 2, 80, 24, 112, 4, 94, 0
Number of data subcarriers in each symbol per subchannel	24	
Number of subchannels	60	
Basic permutation sequence 12 (for 12 subchannels)		6, 9, 4, 8, 10, 11, 5, 2, 7, 3, 1, 0
Basic permutation sequence 8 (for 8 subchannels)	4	7, 4, 0, 2, 1, 5, 3, 6

2.15.2.8 Downlink Subchannels Subcarrier Allocation in PUSC

The carrier allocation to subchannels is performed by using the following procedure, Table 2.11 (for example 2048-FFT):

1. Divide the subcarriers into the number of clusters ($N_{clusters}$) physical clusters containing 14 adjacent subcarriers each (starting from carrier 0). The number of clusters, $N_{clusters}$, varies with FFT sizes (e.g., 120 for 2048 FFT or 60 for 1024 FFT).
2. Renumber the physical clusters into logical clusters using the following formula:

$$LogicalCluster = RenumberingSequence \times (\{PHY_Cluster + 13 * DL_PermBase\} \bmod N_{clusters}) \quad (2.6)$$

where DL_PermBase parameter is an integer ranging from 0 to 31.

1. Divide the clusters into six major groups shown in Table 2.12. These groups may be allocated to segments, if a segment is being used, then at least one group shall be allocated to it (by default group 0 is allocated to sector 0, group 2 is allocated to sector 1, and group 4 to is allocated sector 2).

Table 2.12 Clusters and respective groups

Group	Clusters
Group 0	0–23
Group 1	24–39
Group 2	40–63
Group 4	64–79
Group 5	80–103
Group 6	104–119

2. Allocate carriers to subchannel in each major group is performed by first allocating the pilot carriers within each cluster, and then taking all remaining data carriers within the symbol. First the six major groups are regrouped into 6 sets of 24 groups, with the pilot tones in each constituent logical cluster excluded. Each of the even numbered major groups (i.e., group 0, 2 and 4) contains 12 logical clusters and each of the odd numbered groups (i.e., groups 1, 3 and 5) contains eight logical clusters, with each cluster carrying 12 data subcarriers and two pilot tones. For the even numbered major groups, each cluster is divided into two groups with six data subcarriers each; for the odd numbered major groups, each cluster is divided into three groups with four data subcarriers each.
3. The subcarriers in each of the 24 groups are mapped into six subchannels or four subchannels using the following equation called **permutation formula**.

$$\begin{aligned} \text{subcarrier}(k, s) = & N_{\text{subchannels}} \cdot n_k + \{p_s[n_k N_{\text{subchannels}}] \\ & + \text{DL_PermBase}\} N_{\text{subchannels}} \end{aligned} \quad (2.7)$$

where:

$\text{Subcarrier}(k, s)$	is the subcarrier index of subcarrier k in subchannel s ,
k	is the subcarrier-in-subchannel index from the set $[0 \dots N_{\text{subchannels}}-1]$
s	is the index number of a subchannel, from the set $[0 \dots N_{\text{subchannels}}-1]$,
$N_{\text{subchannels}}$	is the number of subchannels in the current Major group
n_k	$= (k + 13s) \bmod N_{\text{subcarriers}}$
$ps[j]$	is the series obtained by rotating basic permutation sequence cyclically to the left s times,
DL_PermBase	is an integer ranging from 0 to 31, which is set to preamble IDCell in the first zone and determined by the DL-MAP for other zones.

A comparison of subcarrier allocations in the 1024 FFT OFDMA System is presented in Table 2.13. The comparison is performed among DL PUSC, DL FUSC, UL PUSC and DL/UL AMC.

2.15.2.9 Symbol Structure for FUSC

The symbol structure is constructed using pilots, data, and zero subcarriers. The symbol is first allocated with the appropriate pilots and with zero subcarriers, and then all the remaining subcarriers (Table 2.14) are used as data subcarriers which are later divided into subchannels.

There are two variable pilot-sets and two constant pilot-sets. The fixed sets are divided into subset that are used in odd and even symbols respectively. This

Table 2.13 Subcarrier allocations in the 1024 FFT OFDMA system

Parameters	DL PUSC	DL FUSC	UL PUSC	DL/UL AMC
Number of DC subcarriers	1	1	1	1
Number of guard subcarriers, left	92	87	92	80
Number of guard subcarriers, right	91	86	91	79
Number of pilot subcarriers	120	82	420/0	96
Number of data subcarriers	720	768	420/840	768
Number of subchannels	30	16	35	48
Number of data subcarriers in each symbol per subchannel	24	48	12/24	16
Number of clusters	60			
Number of subcarriers per cluster	14			
Number of tiles			210	
Number of subcarriers per tile			4	
Number of tiles per subchannel			6	
Number of bins				96
Number of subcarriers per bin				9
Number of bins per subchannel				2

Table 2.14 OFDMA downlink subcarrier allocations for FUSC

Parameter	Value	Comments
Number of DC subcarriers	1	Index 1024
Number of guard subcarriers, left	160	
Number of guard subcarriers, right	159	
Number of used subcarriers, <i>N_{used}</i>	1,729	Number of all subcarriers used within a symbol, including all possible allocated pilots and the DC carrier
Number of data subcarriers	1,536	
Number of data subcarriers per subchannel	48	
Number of subchannels	32	
PermutationBase		3, 18, 2, 8, 16, 10, 11, 15, 26, 22, 6, 9, 27, 20, 25, 1, 29, 7, 21, 5, 28, 31, 23, 17, 4, 24, 0, 13, 12, 19, 14, 30

provides a tradeoff between allocated power and frequency diversity on pilots for channel estimation. Table 2.15 shows the distribution of fixed and variable sets of pilots for 2048 FFT while Tables 2.16 and 2.17 presents the respective distributions for 1024 FFT and 512 FFT, respectively.

2.15.2.10 Downlink Subchannels Subcarrier Allocation in PUSC

The carrier allocation to subchannels is performed using the following procedure, as shown in Fig. 2.43:

1. Divide the subcarriers into the number of physical clusters ($N_{clusters}$), containing 14 adjacent subcarriers each (starting from carrier 0). The number

Table 2.15 2048-FFT OFDMA downlink carrier allocations – FUSC

Parameter	Value	Comments
Pilot Subcarrier Index: VariableSet #0	71	0,72,144,216,288,360,432,504,576,648,720,792,864, 936,1008,1080,1152,1224,1296,1368,1440,1512,1584, 1656,48,120,192,264,336,408,480,552,624,696,768, 840,912,984,1056,1128,1200,1272,1344,1416,1488, 1560,1632,24,96,168,240,312,384,456,528,600,672, 744,816,888,960,1032,1104,1176,1248,1320,1392, 1464,1536,1608,1680
Pilot Subcarrier Index: ConstantSet #0	12	$72*(2*n + k) + 9$ when $k = 0$ and $n = 0 \dots 5$ DC subcarrier shall be included when the pilot subcarrier index is calculated by the equation
Pilot Subcarrier Index: VariableSet #1	71	36,108,180,252,324,396,468,540,612,684,756, 828,12,84,156,228,300,372,444,516,588,660, 732,804,60,132,204,276,348,420,492,564,636, 708,780
Pilot Subcarrier Index: ConstantSet #1	12	$72*(2*n + k) + 9$ when $k = 1$ and $n = 0 \dots 4$ DC subcarrier shall be included when the pilot subcarrier index is calculated by the equation
Basic Permutation Sequence	–	3, 18, 2, 8, 16, 10, 11, 15, 26, 22, 6, 9, 27, 20, 25, 1, 29, 7, 21, 5, 28, 31, 23, 17, 4, 24, 0, 13, 12, 19, 14, 30

Table 2.16 1024 FFT OFDMA downlink subcarrier allocations – FUSC

Parameter	Value	Comments
Pilot Subcarrier Index: VariableSet #0	12	0, 24, 48, 72, 96, 120, 144, 168, 192, 216, 240, 264, 288, 312, 336, 360, 384, 408, 432, 456, 480, 504, 528, 552, 576, 600, 624, 648, 672, 696, 720, 744, 768, 792, 816, 840
Pilot Subcarrier Index: ConstantSet #0	2	$72*(2*n + k) + 9$ when $k = 0$ and $n = 0 \dots 5$ DC subcarrier shall be included when the pilot subcarrier index is calculated by the equation
Pilot Subcarrier Index: VariableSet #1	12	36, 108, 180, 252, 324, 396, 468, 540, 612, 684, 756, 828, 12, 84, 156, 228, 300, 372, 444, 516, 588, 660, 732, 804, 60, 132, 204, 276, 348, 420, 492, 564, 636, 708, 780
Pilot Subcarrier Index: ConstantSet #1	2	$72*(2*n + k) + 9$ when $k = 1$ and $n = 0 \dots 4$ DC subcarrier shall be included when the pilot subcarrier index is calculated by the equation
Basic Permutation Sequence	–	6, 14, 2, 3, 10, 8, 11, 15, 9, 1, 13, 12, 5, 7, 4, 0

of clusters, $N_{clusters}$, varies with FFT sizes as mentioned in Tables 2.11 and 2.13.

2. Renumber the physical clusters into logical clusters using the following formula:

$$\text{Logical Cluster} = \text{Renumbering Sequence}((\text{Physical Cluster}) + 13 \cdot \text{DL_PermBase}) \quad (2.8)$$

Table 2.17 FFT OFDMA downlink subcarrier allocations – FUSC

Parameter	Value	Comments
Pilot Subcarrier Index: VariableSet #0	18	0, 24, 48, 72, 96, 120, 144, 168, 192, 216, 240, 264, 288, 312, 336, 360, 384, 408
Pilot Subcarrier Index: ConstantSet #0	3	$72*(2*n + k) + 9$ when $k = 0$ and $n = 0 \dots 2$ DC subcarrier shall be included when the pilot subcarrier index is calculated by the equation
Pilot Subcarrier Index: VariableSet #1	18	12, 36, 60, 84, 108, 132, 156, 180, 204, 228, 252, 276, 300, 324, 348, 372, 396, 420
Pilot Subcarrier Index: ConstantSet #1	3	$72*(2*n + k) + 9$ when $k = 1$ and $n = 0 \dots 2$ DC subcarrier shall be included when the pilot subcarrier index is calculated by the equation
Basic Permutation Sequence	–	2, 0, 1, 6, 4, 3, 5, 7

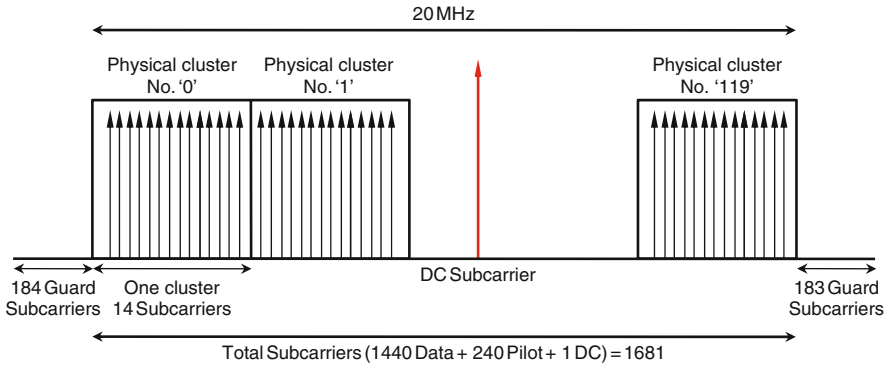


Fig. 2.43 Downlink subchannels subcarrier allocation in PUSC

3. Logical clusters of step 2 are grouped together to form six major groups. These groups are numbered from 0 to 5. The allocation algorithm varies with FFT sizes as follows:
- **FFT size = 2048** – The clusters are divided into six major groups. Group 0 includes clusters 0–23, group 1 includes clusters 24–39, group 2 includes clusters 40–63, group 3 includes clusters 64–79, group 4 includes clusters 80–103, group 5 includes clusters 104–119. These groups may be allocated to segments, if a segment is being used, then at least one group shall be allocated to it (by default group 0 is allocated to sector 0, group 2 is allocated to sector 1, and group 4 is allocated sector 2).
 - **FFT size = 512** – The clusters are divided into six major groups. Group 0 includes clusters 0–9, group 2 includes clusters 10–19, group 4 includes clusters 20–29. These groups may be allocated to segments, if a segment is being used, then at least one group shall be allocated to it (by default group 0 is allocated to sector 0, group 2 is allocated to sector 1, and group 4 to is allocated sector 2).

- **FFT size = 128** – The clusters are divided into six major groups. Group 0 includes clusters 0–1, group 2 includes clusters 2–3, group 4 includes clusters 4–5. These groups may be allocated to segments, if a segment is being used, then at least one group shall be allocated to it (by default group 0 is allocated to sector 0, group 2 is allocated to sector 1, and group 4 to is allocated sector 2).
4. Allocate subcarriers to subchannel in each major group is performed separately for each OFDMA symbol by first allocating the pilot carriers within each cluster, and then taking all remaining data carriers within the symbol and using the **Permutation Formula** defined in FUSC subcarrier allocation. The parameters vary with FFT sizes as follows:
- **FFT size = 2048** – Use the parameters from Table 2.15, with basic permutation sequence 12 for even numbered major groups, and basic permutation sequence 8 for odd numbered major groups, to partition the subcarriers into subchannels containing 24 data subcarriers in each symbol.
 - **FFT size = 1024** – Use the parameters from Table 2.16, with basic permutation sequence 6 for even numbered major groups, and basic permutation sequence 4 for odd numbered major groups, to partition the subcarriers into

2.15.2.11 PUSC UL

One slot of PUSC UL is three OFDM symbols by one subchannel. Out of 2,048, there are 184 left guard subcarriers, 183 right guard subcarriers and one DC subcarrier. There are ‘840 data + 840 pilot’ subcarriers for even numbered OFDM symbols and ‘1680 data + 0 pilot’ for odd numbered OFDM symbols. Figure 2.44 shows how pilots are marked for even numbered OFDM symbols and also it points out the absence of pilot carriers during odd symbol.

2.15.2.12 Adjacent Subcarrier Permutation

OFDMA PHY supports AAS and also a set of second-, third-, and fourth-order transmit diversity options. With the AAS option, the system uses a multiple-

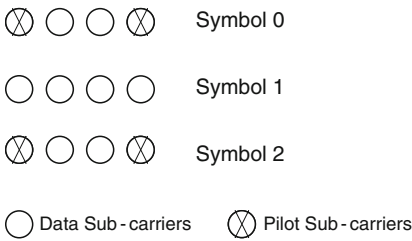


Fig. 2.44 UL PUSC tile structure

antenna transmission to improve the coverage and capacity of the system while minimizing the probability of outage through transmit diversity, beam forming and null steering.

An AAS DL Zone begins on the specified symbol boundary and consists of all subchannels until the start of the next Zone or end of frame. The two highest numbered subchannels of the DL frame may be dedicated at the discretion of the BS for the AAS Diversity-Map Zone in PUSC, FUSC, and optional FUSC permutation. It should be noted that AAS Diversity-Map Zone shall is used only with FFT sizes greater than or equal to 512.

In the AMC permutation, first and last subchannels of the AAS DL Zone may be dedicated at the discretion of the BS for the AAS Diversity-Map Zone as shown in the Fig. 2.45. When first and the last subchannels are used for Diversity-Map zone, they are not allocated in the normal DL-MAP message but are used to transmit the AAS-DLFP(). In case that the AAS Diversity-Map zone is not included in the AAS zone, these subchannels may be used for ordinary traffic and may be allocated in DL_MAP messages.

For all AMC permutations in an AAS zone including the optional AAS Diversity-Map zone, two bin by three symbol tile structure is used. In the AAS zone, the same antenna beam pattern shall be used for all pilot subcarriers and data subcarriers in a given AMC subchannel.

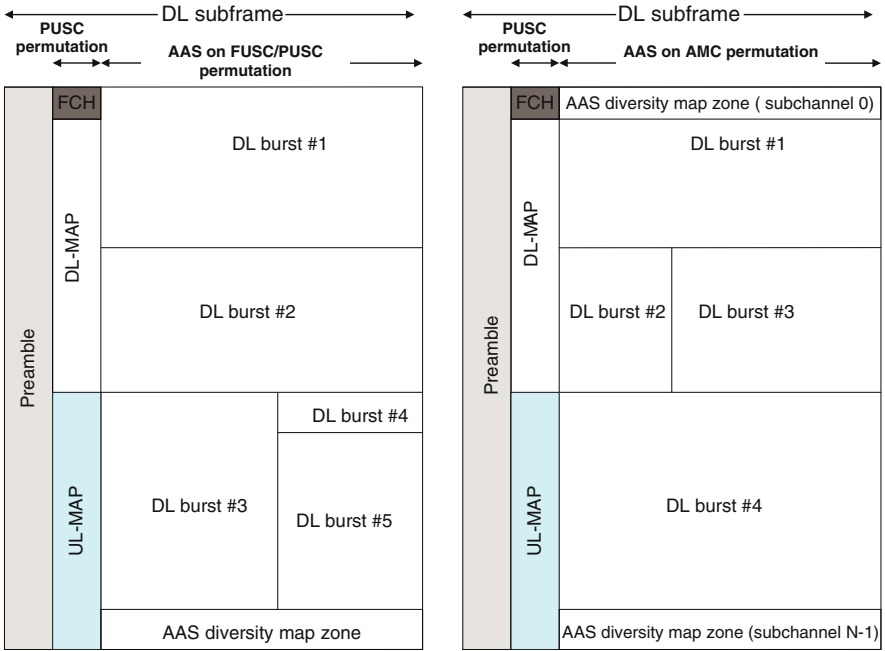


Fig. 2.45 AAS diversity map frame structure

2.15.2.13 Adjacent Subcarrier Permutation

In the case of AMC, the basic allocation unit is bin. Bin is the smallest unit in frequency domain for adjacent carrier per-mutation. It is composed of nine contiguous subcarriers. Out of nine, eight are data tones and one is pilot tone as shown in Fig. 2.46.

SS may switch from the distributed subcarrier permutation to the adjacent subcarrier permutation, when it changes from non-AAS to AAS-enabled traffic to support Adaptive Antenna System (AAS) adjacent subcarrier user traffic. For AMC, permutation is same for UL and DL.

Once switched to the zone of adjacent subcarrier permutation mode in a frame, BS shall continue to transmit/receive data using the adjacent subcarrier permutation mode. The BS shall return to the distributed subcarrier permutation at the beginning of a new DL sub-frame.

2.15.2.14 OFDMA Ranging

In IEEE 802.16e four types of ranging procedure exists: initial ranging, periodic ranging, bandwidth request ranging and handover ranging. Initial and periodic ranging processes are supported to synchronize the SSs with the BS at the initial network entry and also periodically during the normal operation. Bandwidth request mechanism is supported so that SSs can request UL allocations for transmission of data to the BS. Handover ranging is used for ranging against a target BS.

The OFDMA PHY specifies a ranging allocation that can be used for ranging as well as bandwidth request. A ranging channel is composed of one or more groups of six adjacent subchannels, where the groups are defined starting from the first subchannel. Optionally, ranging channel may be composed of eight adjacent subchannels using the symbol structure. Users are allowed to collide on this ranging

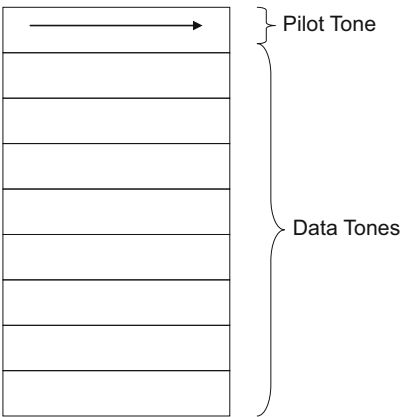


Fig. 2.46 Bin structure in adjacent subcarrier permutation

channel. To effect a ranging transmission, each user randomly chooses one ranging code from a bank of specified binary codes. These codes are then BPSK modulated onto the subcarriers in the ranging channel, one bit per subcarrier. The initial ranging transmission is used by any SS that wants to synchronize to the system channel for the first time.

An initial-ranging transmission is performed during two or four consecutive symbols. The same ranging code is transmitted on the ranging channel during each symbol, with no phase discontinuity between the two symbols. A time-domain illustration of the initial-ranging/handover-ranging transmission is shown in Fig. 2.47.

The BS can allocate two consecutive initial-ranging/handover-ranging slots, Fig. 2.48. The SS then transmits the two consecutive initial-ranging/handover-ranging codes. The SS can also optionally use two consecutive ranging codes transmitted during a four-OFDM symbol period. This option decreases the probability of failure and increases the ranging capacity to support larger numbers of

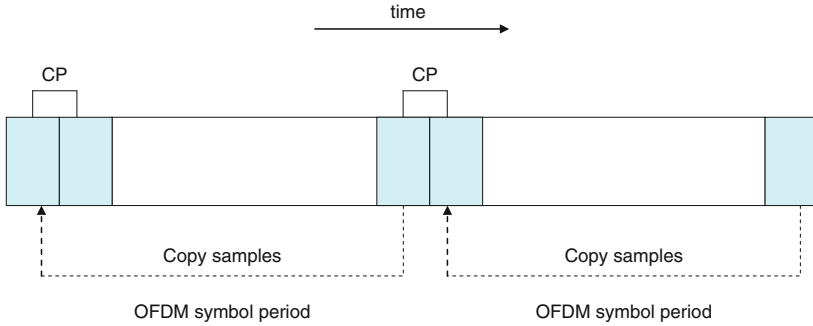


Fig. 2.47 Initial ranging transmissions for OFDMA (adapted from [23])

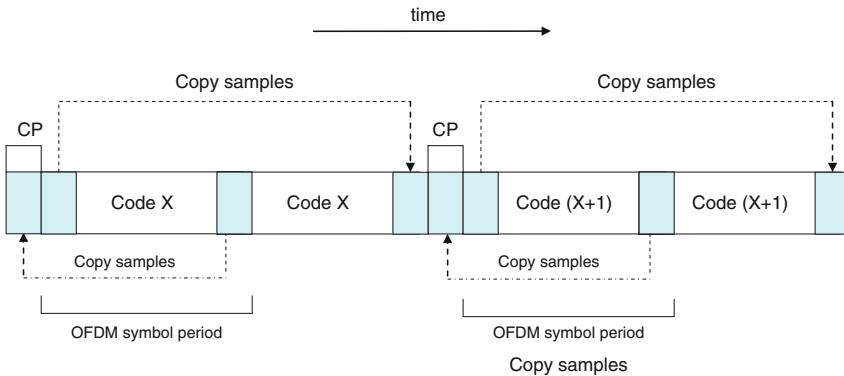


Fig. 2.48 Initial ranging transmission for OFDMA, using two consecutive initial ranging codes

simultaneous ranging SSs while at the same time it further increases the capability of the system to support larger numbers of synchronization mismatches [35]. For this the starting code should always be multiple of 2.

2.15.2.15 Ranging Codes

The ranging codes are binary pseudo-noise codes produced by the PRBS generator. A set of 256 special pseudo-noise 144 bit-long ranging codes are divided into four groups for Initial Ranging, Periodic Ranging, Bandwidth Requests and Handover Ranging such that the BS can determine the purpose of the received code by the subset to which the code belongs. From the available codes, the first N are for initial ranging, the next M are for periodic ranging, the next L for bandwidth request and the remaining S ($S = 144 - N - M - L$) are for Handover ranging [30, 36].

2.15.2.16 Channel Coding

For OFDMA PHY, channel coding procedures include randomization, FEC encoding, bit interleaving, and modulation.

As shown in the Fig. 2.49, the basic block pass the regular coding chain where the first subchannel set the randomization seed, and the data follow the coding chain up to the mapping. The output data from the modulation is mapped onto the block of subchannels allocated for the basic block. Then, it is also mapped on the allocated subchannels.

2.15.2.17 Randomization

Data randomization is performed on all data transmitted on the downlink as well as uplink except the FCH. The randomization is initialized on each FEC block. If the amount of data to transmit does not fit exactly the amount of data allocated, padding of 0xFF (“1” only) shall be added to the end of the transmission block, up to the amount of data allocated. Here, the amount of data allocated means the amount of data that corresponds to the amount of $[N_s/R]$ slots, where N_s is the number of the slots allocated for the data burst and R is the repetition factor used.



Fig. 2.49 Channel coding process for regular and repetition coding transmission

2.15.2.18 Encoding

The encoding block size depends on the number of slots allocated and the modulation specified for the current transmission. Concatenation of a number of slots is performed in order to make larger blocks of coding where it is possible, with the limitation of not exceeding the largest supported block.

The OFDMA PHY supports mandatory tail-biting Convolutional Coding and three optional coding schemes. Zero Tailing Convolutional code, Convolutional Turbo code along with HARQ, and Block Turbo code are the optional coding schemes.

The tail biting is implemented by initializing the encoders memory with the last data bits of the FEC block being encoded, and the zero tailing is implemented by appending a zero tail byte to the end of each burst.

HARQ mitigates the effect of impairments due to channel and external interference by effectively employing time diversity along with incremental transmission of parity codes (subpackets in this case). In the receiver, previously erroneously decoded subpackets and retransmitted subpackets are combined to correctly decode the message. The transmitter decides whether to send additional subpackets, based on ACK/NAK messages received from the receiver.

2.15.2.19 Bit Interleaving

Bit interleaving is done in order to protect the transmission against long sequences of consecutive errors, which are very difficult to correct. Interleaving process is performed on encoded data at the output of FEC. The size of the interleaving block is based on the number of coded bits per encoded block size. The interleaving is performed using a two-step permutation process. The first permutation ensures that adjacent coded bits are mapped onto nonadjacent subcarriers and the second permutation ensures that adjacent coded bits are mapped alternately onto less or more significant bits of the constellation, thus avoiding long runs of lowly reliable bits.

2.15.2.20 Repetition

The Repetition process was added in Channel Coding in IEEE 802.16e standard for PFDMA PHY [24]. Repetition coding is used to further increase signal margin over the modulation and FEC mechanisms.

In the case of repetition coding, $R = 2, 4, \text{ or } 6$, the number of allocated slots (N_s) will be a whole multiple of the repetition factor R for uplink. For the downlink, the number of the allocated slots (N_s) will be in the range of $R \times K, R \times K + (R-1)$, where K is the number of the required slots before applying the repetition scheme. For example, when the required number of slots before the repetition is $10 (= K)$ and the repetition of $R = 6$ will be applied for the burst transmission, then the number of the allocated slots (N_s) for the burst can be from 60 slots to 65 slots.

The binary data that fits into a region that is repetition coded is reduced by a factor R compared to a non-repeated region of the slots with the same size and FEC code type. After FEC and bit-interleaving, the data is segmented into slots, and each group of bits designated to fit in a slot will be repeated R times to form R contiguous slots following the normal slot ordering that is used for data mapping.

This repetition scheme applies only to QPSK modulation; it can be applied in all coding schemes except HARQ with CTC.

2.16 Summary and Conclusions

This Chapter covers aspects of OFDM and OFDMA WiMAX physical layer. It started by presenting the historical evolution of OFDM, OFDM fundamentals and the OFDM transmission concept, including details on the serial to parallel converter and the role of the demodulator. The OFDM symbol time structure was presented and ISI and ICI mitigation was discussed together with details on OFDM spectral efficiency and the impact of subchannelisation, which shows the advantages of OFDM. Robustness against narrowband interference, simple equalisation, low cost transmitter, simple receiver, sub-carrier rate adaptation and resistance against selective fading are amongst the advantages of OFDM.

The parameters and principles of Scalable OFDMA were also addressed and its usefulness in IEEE 802.16e was highlighted, as it enables that IEEE 802.16e may be backward compatible with FBWA IEEE 802.16-2004. Finally, the IEEE 802.16 PHY layer was described in detail, including aspects of WirelessMAN-SC, WirelessMAN-OFDM, WirelessMAN-OFDMA and WirelessMAN-HUMAN PHYs.

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WiMAX Networks

Techno-Economic Vision and Challenges

Prasad, R.; Velez, F.J.

2010, XXVII, 488 p., Hardcover

ISBN: 978-90-481-8751-5