CHAPTER 8

ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Present an overview of OFDM, OFDMA, and SC-FDMA.
- Show how OFDM combats frequency selective fading.
- Explain the value of orthogonal carriers.
- Show the reduction in number of oscillators needed when using the IFFT.
- Explain the problems of the peak-to-average power ratio (PAPR).
- Explain how multiple access is achieved using OFDM and SC-FDMA.

This chapter introduces **orthogonal frequency division multiplexing (OFDM)**-based techniques that have created great expansion in the capacity of wireless networks. OFDM is the main air interface technology used to move from third- to fourth-generation cellular technologies. OFDM also allows the expansion of IEEE 802.11 data rates. Finally, OFDM is a critical technology in the development of broadband wireless Internet access for both fixed and mobile systems under the WiMAX standard. We first look at the basic mechanisms of OFDM, namely, orthogonal carriers and transmitter design based on the inverse fast Fourier transform. Then we look at the ways OFDM is used in practical systems for multiple access topics and the methods to address OFDM problems, especially peak-to-average power ratio (PAPR) and intercarrier interference issues. This chapter discusses fundamental principles; more details about the implementation of OFDM for specific technologies are given in the discussions of IEEE 802.11 Wi-Fi, LTE, and WiMAX in Chapters 11, 14, and 16.

8.1 ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

OFDM, also called *multicarrier modulation*, uses multiple carrier signals at different frequencies, sending some of the bits on each channel. This is similar to frequency division multiplexing (FDM). However, in the case of OFDM, many subcarriers are dedicated to a single data source.

Figure 8.1 illustrates a conceptual understanding of OFDM. Actual transmitter operation is simplified, but the basic concept can first be understood here. Suppose we have a binary data stream operating at R bps and an available bandwidth of Nf_b, centered at f_0. The entire bandwidth could be used to send the data stream, in which case each bit duration would be $\frac{1}{R}$. The alternative is to split the data stream into N substreams, using a serial-to-parallel converter. Each substream has a data rate of R/N bps and is transmitted on a separate subcarrier, with a spacing between adjacent subcarriers of f_b. Now the bit duration is N/R, which is substantially longer and creates special capabilities to overcome multipath fading.

Orthogonality

To gain a clearer understanding of OFDM, let us consider the scheme in terms of its base frequency, f_b. This is the lowest-frequency subcarrier. All of the other subcarriers are integer multiples of the base frequency, namely, $2f_b$, $3f_b$, and so on,

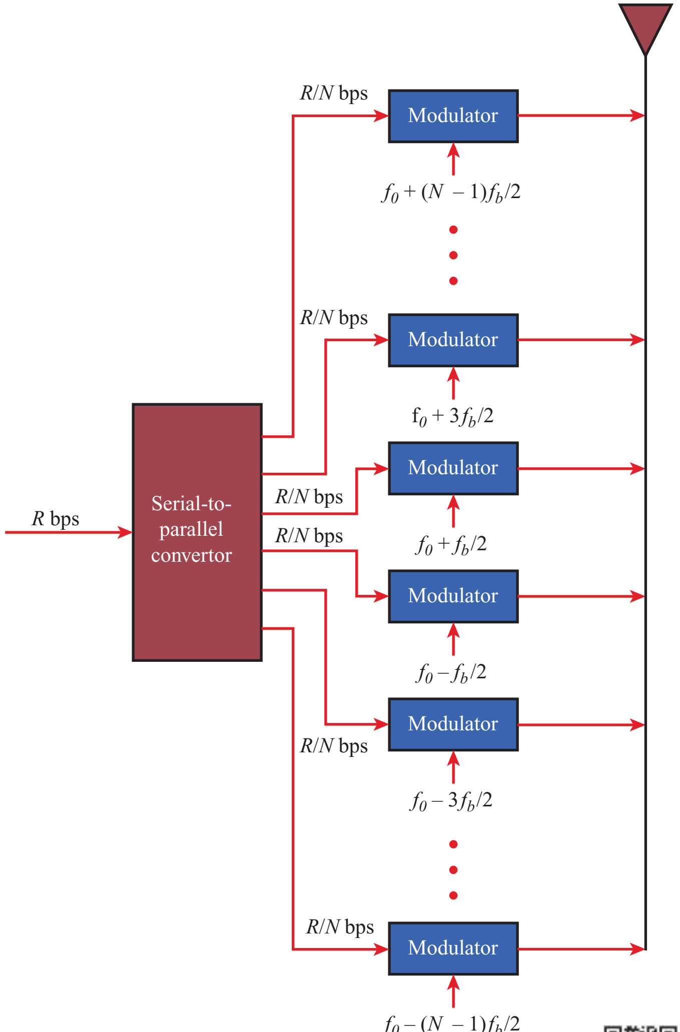


Figure 8.1 Conceptual Understanding of Orthogonal Frequency Division Multiplexing

as shown in Figure 8.2. The OFDM scheme uses advanced digital signal processing techniques to distribute the data over multiple carriers at precise frequencies. The relationship among the subcarriers is referred to as **orthogonality**. The result is shown in Figure 8.2b. It looks like the signals are packed too close together because they overlap substantially, but one property of orthogonality is that the peaks of the power spectral density of each subcarrier occur at a point at which the power of other subcarriers is zero. Previous FDM approaches are illustrated in Figure 8.2c, which assumed signals should be spaced sufficiently apart in frequency to (1) avoid overlap in the frequency bands and (2) to provide extra spacing known as *guard bands* to prevent the effects of adjacent carrier interference from out-of-band

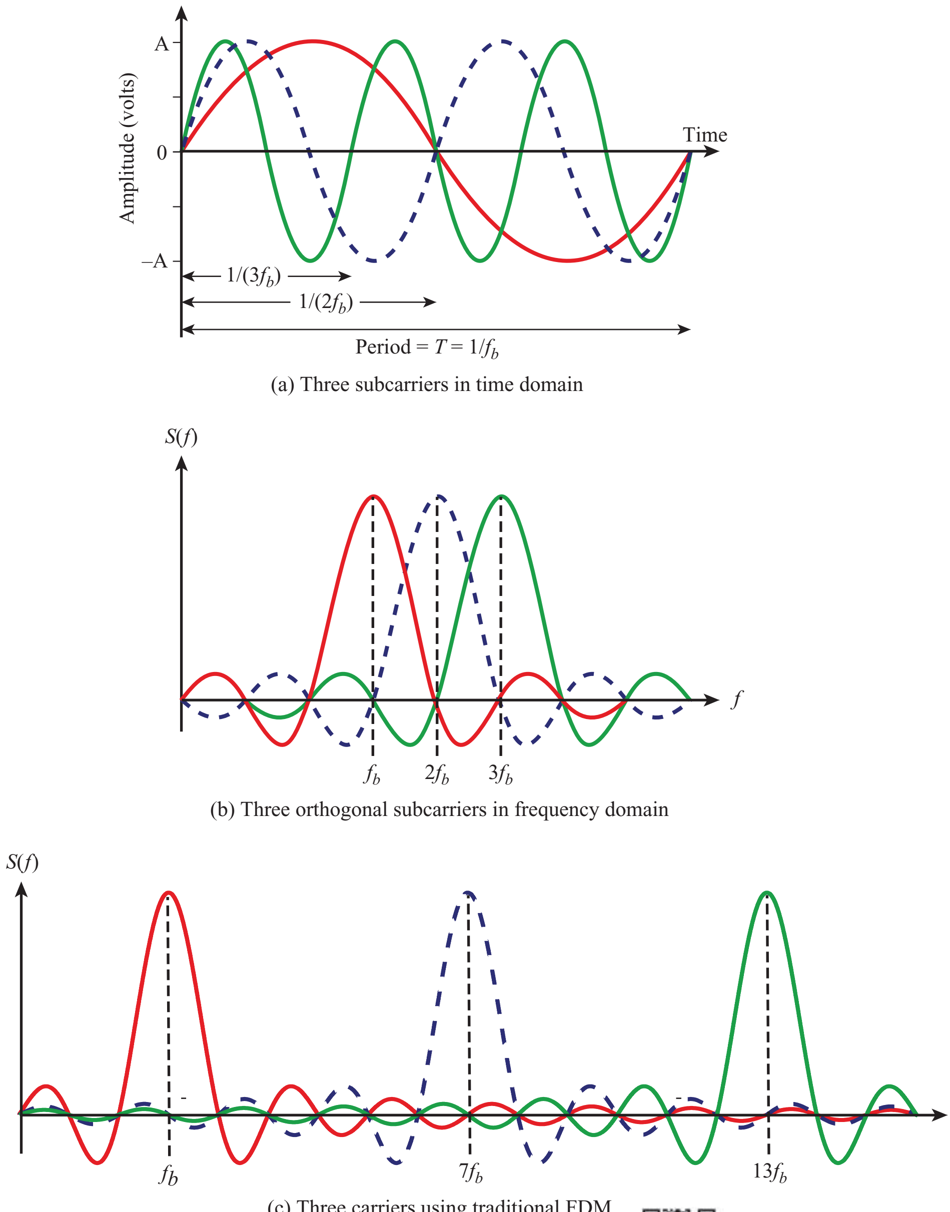


Figure 8.2 Illustration of Orthogonality of OFDM

emissions. But OFDM is able to drastically improve the use of frequency spectrum. Viewing Figure 8.2b compared to 8.2c, the number of signals that can be supported has increased by a factor of 6!

With OFDM, the subcarriers can be packed tightly together because there is minimal interference between adjacent subcarriers (zero interference if the carrier spacing is not corrupted). Orthogonality is defined by an important mathematical principle. Two signals, $s_1(t)$ and $s_2(t)$, are orthogonal if they meet this requirement.

$$\text{Average over bit time of } s_1(t)s_2(t) = 0$$

At the transmitter, we send the signal

$$s(t) = s_1(t) + s_2(t)$$

At the receiver intended to extract the $s_1(t)$ signal from the received signal, it multiplies by $s_1(t)$ and averages. If the signals are orthogonal, here is the result.

$$\text{Average over bit time of } s_1(t)s(t) = s_1(t)s_1(t) + s_1(t)s_2(t) = s_1^2(t) + 0$$

The output is only the intended $s_1(t)$ squared and the $s_2(t)$ is removed. If there are many signals that are all orthogonal, the receiver can remove all of the other signals and only again have $s_1(t)$.

Here is the requirement for orthogonal digital signals that are subcarriers of OFDM. If the bit time of a subcarrier is T, then the base frequency f_b must be chosen to be a multiple of $\frac{1}{T}$. Every other signal will be a multiple of f_b such that $Mf_b = \frac{M}{T}$ for some integer M. All the signals will be orthogonal. One example of OFDM is that used for fourth-generation cellular LTE technology which uses a subcarrier spacing of 15 kHz.

Note that Figure 8.2 depicts the set of OFDM subcarriers in a frequency band beginning with the base frequency. For transmission, the set of OFDM subcarriers is further modulated to a higher frequency band. For example, the OFDM scheme in the IEEE 802.11n wireless LAN standard consists of 48 subcarriers over a 20 MHz channel or 108 subcarriers for a 40 MHz channel with a base frequency of $f_b = 0.3125$ MHz. This set of subcarriers is then translated to 2.4-GHz or 5-GHz range for transmission.

Benefits of OFDM

OFDM has several advantages. First, frequency selective fading only adversely affects some subcarriers and not the whole signal. If the data stream is protected by a forward error-correcting code, this type of fading is easily handled. More important, OFDM overcomes intersymbol interference (ISI) in a multipath environment. As discussed in Chapter 3, ISI has a greater impact at higher bit rates; because the distance between bits, or symbols, is smaller, the expansion of time due to multipath easily interferes with subsequent bits. With OFDM, the data rate per carrier is reduced by a factor of N, which increases the symbol time by a factor of N. Thus, if the symbol period is T_s for the source stream, the period for the OFDM signals is NT_s. This dramatically reduces the effect of ISI because the symbols are substantially longer. As a design criterion, N is chosen so that NT_s is significantly greater than the root-mean-square delay spread of the channel. Even the spread in the time delays of the multipath components does not affect the signal substantially.

As a result of these considerations, with the use of OFDM, it may not be necessary to deploy equalizers to counteract ISI. Equalizers are complex and expensive devices whose complexity increases with the severity of the ISI.

OFDM Implementation

OFDM implementation has two important operations that are involved to create the benefits just described. These are use of the inverse fast Fourier transform (IFFT) and cyclic prefix (CP).

Inverse Fast Fourier Transform Even though OFDM dates back some 40 years, it was only until the 1990s that an advance was made to make OFDM an economical technology. Figure 8.1 showed a conceptual understanding of OFDM where a data stream is split into many lower bit rate streams and then modulated on many different subcarriers. Such an approach, however, would result in a very expensive transmitter and receiver because it would have some many expensive oscillators.

Fortunately, OFDM can instead be implemented by taking advantage of the properties of the **discrete Fourier transform (DFT)** which refers to any algorithm that generates a quantized Fourier transform, $X[k]$, of a discrete time-domain function, $x[n]$.

$$X[k] = \sum_{n=0}^{N-1} x[n] e^{-j\frac{2\pi kn}{N}}$$

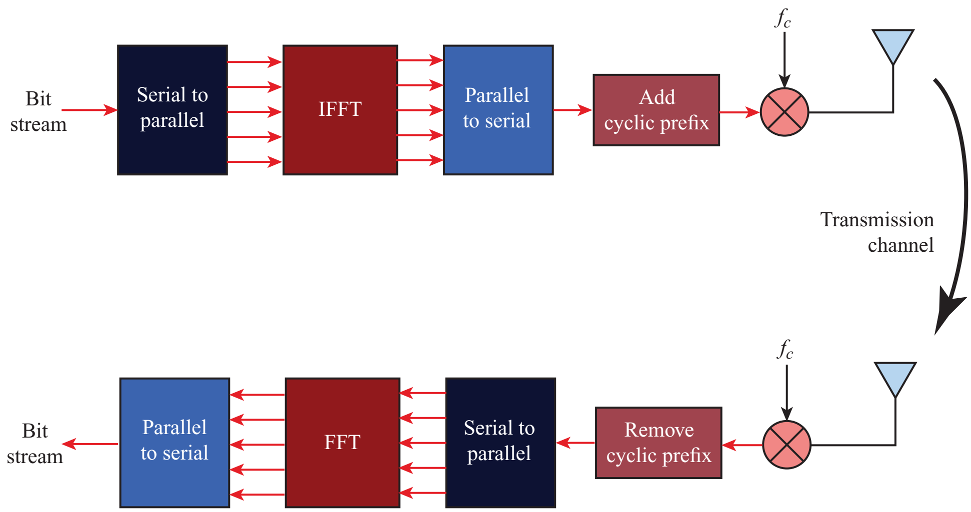
The inverse discrete Fourier transform, which converts the frequency values back to time domain values, is as follows.

$$x[n] = \sum_{n=0}^{N-1} X[k] e^{j\frac{2\pi kn}{N}}$$

When this function is implemented using a number of data points N that is a power of two, the computational time is greatly reduced and these then are called the **fast Fourier transform (FFT)** and **inverse fast Fourier transform (IFFT)**.

The implementation of OFDM using the FFT and IFFT is illustrated in Figure 8.3. The data stream undergoes a serial to parallel (S/P) operation, which takes a sample from each carrier and makes a group of samples called an ***OFDM symbol***. Each value in a sense gives a weight for each subcarrier. Then the IFFT (not FFT) takes the values for these subcarriers and computes the time domain data stream to be transmitted, which is a combination of these subcarriers. The IFFT operation has the effect of ensuring that the subcarriers do not interfere with each other. These values are put back into a serial stream with a P/S operation, then the stream is modulated onto the carrier using one oscillator. At the receiver, the reverse operation is performed. An FFT module is used to map the incoming signal back to the M subcarriers, from which the data streams are recovered as the weights for each subcarrier are retrieved for each sample.

Note that in OFDM the term "symbol" takes on a different meaning than is used in other contexts. This might at first be confusing. In Chapter 7, we referred to a symbol as a point in a signal constellation diagram that could be used to transmit multiple bits per symbol. Here, an OFDM symbol is a group of samples, one from each subcarrier. This is the input to the IFFT operation. It is, therefore, entirely possible that if one were using a 16QAM modulation scheme and an OFDM block



FFT = fast Fourier transform
IFFT = inverse fast Fourier transform

Figure 8.3 IFFT Implementation of OFDM

size of eight samples, one would be transmitting an OFDM symbol of 8 16 quadrature amplitude modulation (QAM) symbols!

The Cyclic Prefix Even though OFDM by definition limits ISI by using long symbol times, OFDM also uses a **cyclic prefix** which goes another step further to combat ISI and completely eliminate the need for equalizers. The cyclic prefix is illustrated in Figure 8.4. The X_i values are the OFDM symbols. This accomplishes two functions:

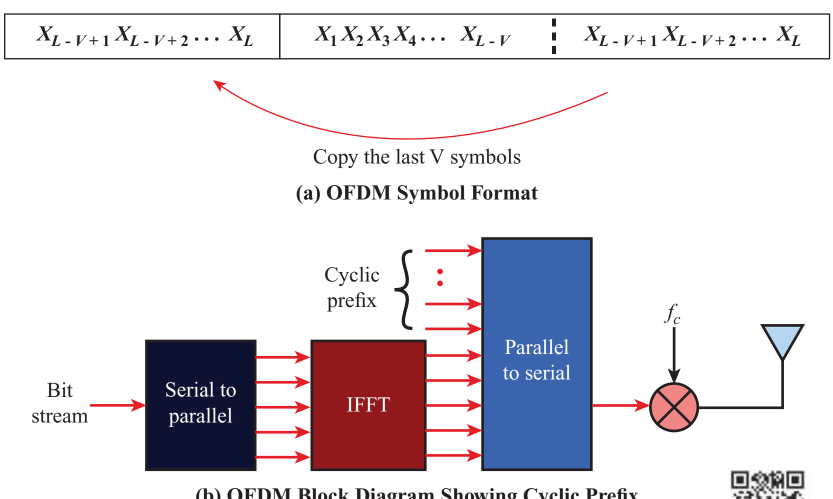


Figure 8.4 Cyclic Prefix

1. Additional time, known as a guard interval, is added to the beginning of the OFDM symbol before the actual data begins. This allows all residual ISI to diminish before it impacts the received data.
2. This beginning time period is packed with data that is an actual copy of the data from the *end* of the OFDM symbol which is being sent. This converts the mathematics of the signal processing into a *circular* operation instead of a linear one. This isolates the parallel subchannels and allows for simple frequency domain digital signal processing techniques.

Example 8.1 Consider an OFDM implementation in the LTE cellular standard. LTE uses 15 kHz subcarriers and can use an OFDM symbol of 1024 subcarriers. The *nominal cyclic prefix* can account for a 7% guard time; the *extended cyclic prefix* can use up to 25%. 600 subcarriers can be used for data transmission. The rest are needed for pilot and null subcarriers. The nominal CP adds $0.07 \times 1024 = 72$ guard symbols, and the extended CP adds $0.25 \times 1024 = 256$ guard symbols. For a transmission bandwidth of 10 MHz and 16 QAM modulation (4 bits/symbol), the data rate for the nominal and extended CPs would be

$$R_{\text{nominal}} = 10\ MHz \frac{600\ data\ subcarriers}{1024 + 72\ total\ symbols}(4) = 21.9\ Mbps$$

$$R_{extended} = 10\ MHz \frac{600\ data\ subcarriers}{1024 + 256\ total\ symbols}(4) = 18.8\ Mbps$$

Difficulties of OFDM

Even though OFDM has tremendous benefits and the implementation process has been highly simplified, there are still two key issues that must be addressed for successful OFDM implementation.

Peak-to-Average Power Ratio (PAPR) OFDM signals have a higher **peak-to-average power ratio (PAPR)** than single-carrier signals because, in the time domain, a multicarrier signal is the sum of many narrowband signals. At some time instances, this sum is large and at other instances it is small, which means that the peak value of the signal is substantially larger than the average value. This is one of the most important challenges for implementation of OFDM because it increases the cost of power amplifiers.

The objective of a power amplifier is to increase the amplitude of a signal by some factor K. This would result in an equation of the relationship between input and output voltage as follows:

$$V_{out} = KV_{in}$$

This is an equation of the line in Figure 8.5 labeled as the ideal amplifier. Ideally this relationship would exist for all input voltages, but instead all amplifiers have a nonlinear region where the amplifier saturates, meaning it cannot produce any higher output voltage regardless of the input voltage. This is indicated by the practical amplifier curve in Figure 8.5. Up until the input voltage is 3 V, the curve is linear,

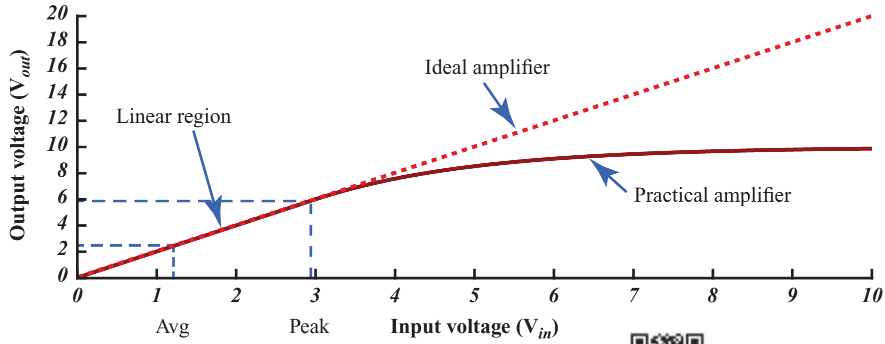


Figure 8.5 Ideal and Practical Amplifier Characteristics

but subsequently the curve becomes nonlinear and the amplifier cannot produce an output beyond 10 V regardless of the input voltage.

Figure 8.6 illustrates the effect that such an amplifier as shown in Figure 8.5 has on output signals. Figure 8.6a shows two signals with amplitudes of 20 V and 2 V, respectively. Figure 8.6b shows the output signals with the smaller signal amplified by a factor of 2 with no distortion. The larger signal, however, has experienced clipping from the amplifier. The signal has now been distorted. If such distortion is

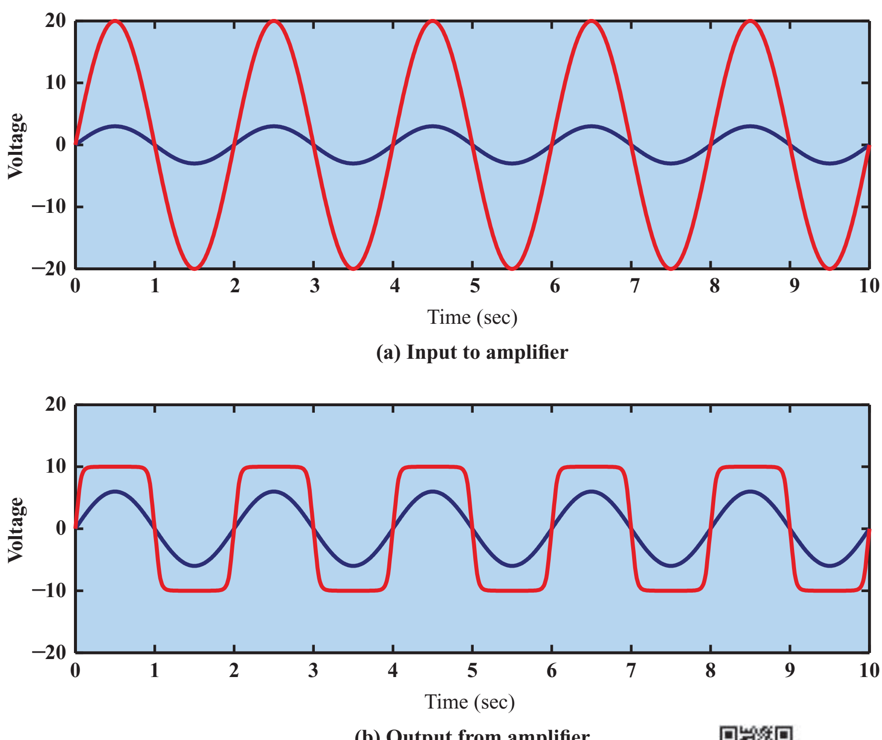


Figure 8.6 Examples of Linear and Nonlinear Amplifier Output

present in OFDM systems, the result will be loss of orthogonality, out-of-band emissions, and increased bit error rate (BER).

Using amplifiers with a long linear range is needed for signals with a wide range of amplitudes as in the OFDM PAPR problem. Such amplifiers are significantly more expensive, however. Another simplistic solution would be to limit the maximum signal amplitude within the linear range of the amplifier. This is called *input backoff*. But this would reduce the power efficiency of the system, decrease signal to interference plus noise ratio (SINR), and reduce coverage.

It is, therefore, important to instead reduce the actual PAPR in the OFDM signal. This is especially true in the uplink from a mobile to a base station. For the downlink, more expensive approaches and amplifiers could be used, because base stations are small in number, but mobiles are many in number and sensitive to cost. PAPR reduction techniques that have been suggested include specialized coding, phase adjustments, clipping using Gaussian functions, and active constellation extension. Systems like LTE have used single-carrier frequency division multiple access (SC-FMDA), which is discussed in a subsequent section.

Intercarrier Interference In order to demodulate an OFDM signal, time and frequency synchronization is necessary. Because OFDM symbol times are long, the demands on time synchronization are somewhat relaxed compared to other systems. But conversely, because OFDM frequencies are spaced as closely as possible, the frequency synchronization requirements are significantly more stringent. If not met, **intercarrier interference (ICI)** will result. Timing and frequency synchronization algorithms are the responsibility of each equipment manufacturer, and these problems are some of the most challenging for OFDM implementation.

The cyclic prefix provides an excellent way of ensuring orthogonality of carriers because it eliminates the effects of multipath. Because the CP causes a reduction in spectral efficiency, however, a certain level of ICI may be tolerated in an effort to reduce CP length. In addition, Doppler shift or mismatched oscillators of even one subcarrier can cause ICI in many adjacent subcarriers. Refer again to Figure 8.2. It is readily seen that the spacing between subcarriers has tight constraints and can be easily perturbed.

Because ICI can be a limiting factor for OFDM systems, implementations will seek to find a balance between carrier spacing and OFDM symbol length. Short symbol duration will reduce Doppler-induced ICI, but also may cause the CP to be an unacceptably large part of the OFDM symbol time. Systems may also use different OFDM pulse shapes, use self-interference cancellation by modulating information across multiple carriers to reduce ICI, and implement frequency domain equalizers.

8.2 ORTHOGONAL FREQUENCY DIVISION MULTIPLE ACCESS (OFDMA)

Multiple access strategies share a wireless channel by making use of scheduled times (time division multiple access), random access times (carrier sense multiple access), scheduled use of frequencies (frequency division multiple access), coded spreading of signals (direct sequence spread spectrum), and/or coded frequency hopping of signals (frequency hopping spread spectrum). Throughout this text, one of the defining attributes of a technology is how it accomplishes multiple access, both in terms of the approaches just mentioned and the protocols that are used for mobile devices to cooperate.

Orthogonal frequency division multiple access (OFDMA) uses a combination of FDMA and TDMA by allowing different users to use a subset of the subcarriers at different times. All technologies that use OFDM do not use OFDMA. For example, some forms of 802.11 use OFDM for the signal transmission, but CSMA for multiple access. The transmitter uses the full set of subcarriers when transmitting. LTE only uses OFDMA on the downlink, but instead uses a single-carrier approach on the uplink.

OFDMA uses OFDM, which employs multiple closely spaced subcarriers, but the subcarriers are divided into groups of subcarriers because it would not be computationally feasible (because of hundreds of subcarriers) or sufficient (because each subcarrier only carries a small capacity) to schedule by individual subcarrier. Each group is named a subchannel. In the downlink, a subchannel may be intended for different receivers. In the uplink, a transmitter may be assigned one or more subchannels. Subchannelization in the uplink can save user device transmit power because it can concentrate power only on certain subchannel(s) allocated to it. This power-saving feature is particularly useful for battery-powered user devices, the likely case in mobile 4G. Figure 8.7 contrasts OFDM and OFDMA; in the OFDMA case the use of adjacent subcarriers to form a subchannel is illustrated. Subchannels can be formed using three different methods:

- **Adjacent subcarriers:** All subcarriers could be assigned in a contiguous block of frequencies. All of the SINRs would be approximately equal. This could be a problem if those frequencies had poor performance, but this also provides

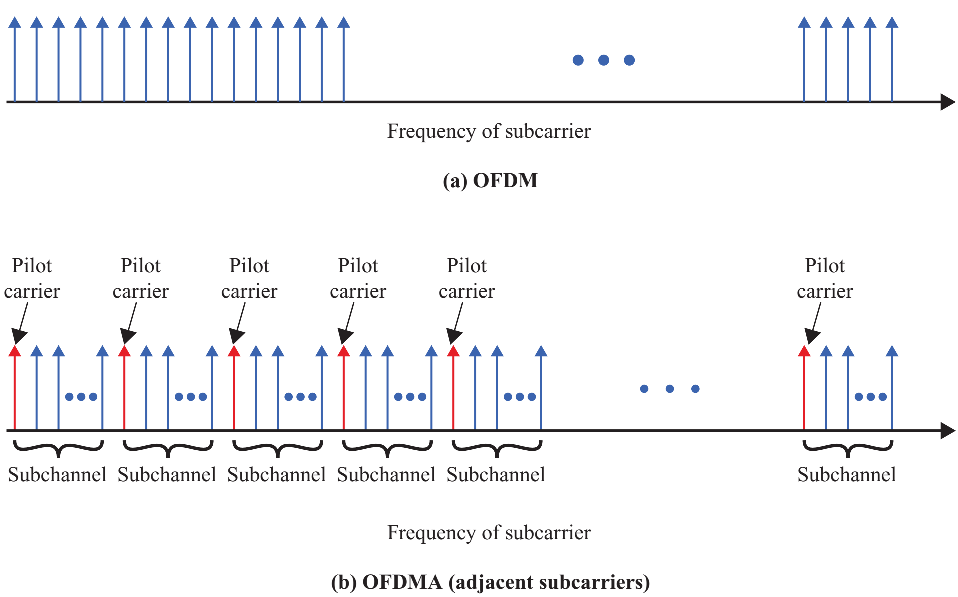


Figure 8.7 OFDM and OFDMA

an opportunity if the system can choose across many possible blocks to find the best allocation of blocks to different users that could optimize a balance of channel efficiency, user requirements, priority, and fairness. This approach, however, requires the system to accurately know the propagation channel over the full system bandwidth for each user, and adapt as those characteristics change. This requires pilot symbols and signals, and also prediction mechanisms because the information could already be out-of-date when it is received and fully processed. This approach can be used by LTE and WiMAX.

- **Regularly spaced subcarriers:** These can be thought of as "distributed" or "comb" allocation. This provides frequency diversity so that there are a sufficient number of good subcarriers, regardless of which are chosen. The burden of channel estimation is not as significant. This approach can also be used by LTE.
- **Randomly spaced subcarriers:** This has similar benefits to regularly spaced subcarriers, but it also has benefits from reduced adjacent-cell interference. This can also be used by WiMAX.

Opportunistic Scheduling

Subchannelization defines subchannels, called ***Resource Blocks*** by LTE, which can be allocated to subscriber stations (SSs) depending on their channel conditions and data requirements. Particular power levels could also be prescribed to those stations in order to optimize throughput and limit interference.

One might think that the time-varying and multipath nature of wireless communications would limit the ability for effective use of the wireless channel, but the opposite is actually true. Such variations provide opportunities that can be exploited. Because channel conditions change and are expected to change, resource allocations can adjust in a dynamic fashion. Hence, the term **opportunistic scheduling** has been used. Particular implementations and equipment providers can approach this problem in ways that provide them competitive advantage, because most standards do not prescribe OFDMA scheduling approaches. There are a variety of considerations when scheduling such subchannels.

- **Efficiency:** One could schedule subchannels based on the users with the highest SINR for that time slot. Those users could use adaptive modulation and coding to obtain much higher throughput than others with poorer SINR. The total efficiency and capacity would be highest; the time-varying nature of the channel would be exploited to the highest benefit.
- **Fairness:** If is scheduling only based on efficiency, however, some users (likely those far from base stations) would receive little or no throughput. Fairness could also be a consideration. A completely fair allocation might give the same number of subchannels or the same throughput to all users, but this could sacrifice efficiency. A popular approach that finds a compromise is known as **proportional fairness**, in which every user computes the following metric during a resource allocation decision:

$$\text{Proportional fairness metric} = \frac{r_i}{\bar{r}_i}$$

This is the ratio of the rate that could be obtained for user i in that time slot for that subchannel, r_i, divided by the average rate that has been obtained for user i in that subchannel, $\bar{r}_i$. In essence, users are compared against themselves and not against others. Those which have a good opportunity *for them* will have a better chance at being scheduled.

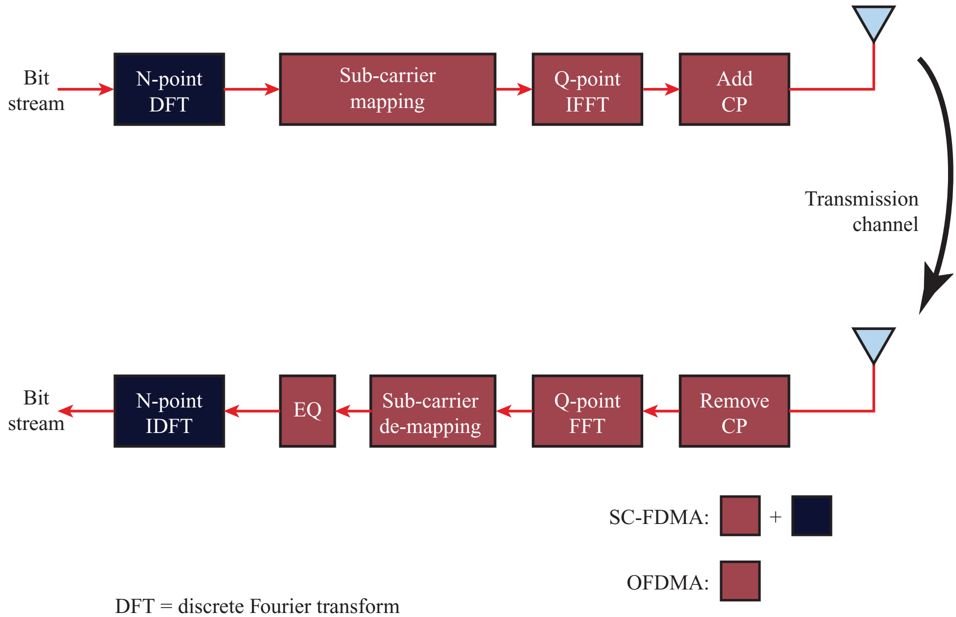
- **Requirements:** Applications such as audio and video may have requirements on delay and jitter. These should be considered.
- **Priority:** Priority users such as police, fire, ambulance, or other public safety workers could need special priorities in emergency situations, regardless of their channel conditions. Note, however, that even for those users their channel conditions may improve significantly within a few milliseconds.

8.3 SINGLE-CARRIER FDMA

Single-carrier FDMA (SC-FDMA) is a relatively recently developed multiple access technique which has similar structure and performance to OFDMA. One prominent advantage of SC-FDMA over OFDMA is the lower PAPR of the transmit waveform, which benefits the mobile user in terms of battery life, power efficiency, and lower cost. Even though the term "single-carrier FDMA" sounds similar to basic OFDM, it is not the same because it performs an extra DFT operation and frequency equalization operation on transmitter and receiver. SC-FDMA is used on the uplink and OFDMA is still used on the downlink for greater multiple access possibilities.

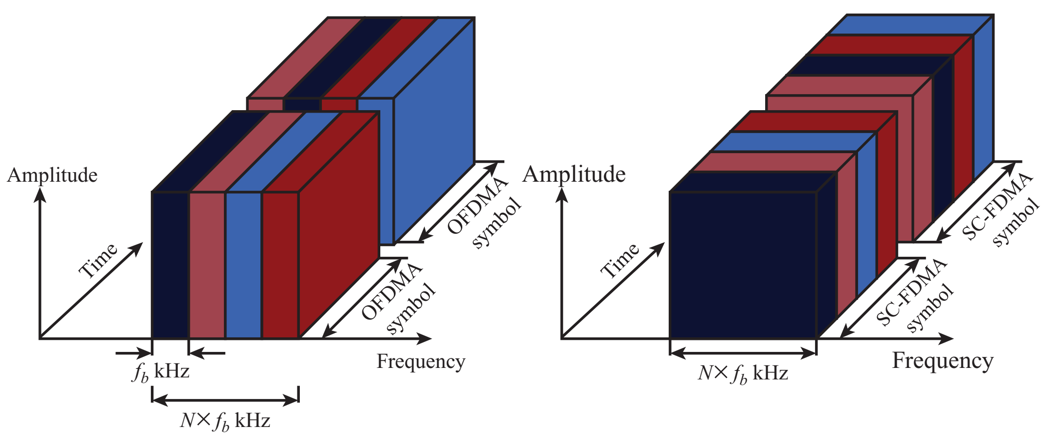
As shown in Figure 8.8, SC-FDMA performs a DFT prior to the IFFT operation, which spreads the data symbols over all the subcarriers carrying information and produces a virtual single-carrier structure. This then is passed through the OFDM processing modules to split the signal into subcarriers. Now, however, every data symbol is carried by every subcarrier. Figure 8.9 is an example of how the OFDM and SC-FDMA signals appear.

With Figure 8.9 in mind, we can make several observations. For OFDM, a source data stream is divided into N separate data streams and these streams are modulated and transmitted in parallel on N separate subcarriers each with bandwidth f_b. The source data stream has a data rate of R bps, and the data rate on each subcarrier is R/N bps. For SC-FDMA, it appears from Figure 8.9 that the source data stream is modulated on a single carrier (hence the SC prefix to the name) of bandwidth $N \times f_b$ and transmitted at a data rate of R bps. The data is transmitted at a higher rate, but over a wider bandwidth compared to the data rate on a single subcarrier of OFDM. However, because of the complex signal processing of SC-FDMA, the preceding description is not accurate. In effect, the source data stream is replicated N times, and each copy of the data stream is independently modulated and transmitted on a subcarrier, with a data rate on each subcarrier of R bps. Compared with OFDM, we are transmitting at a much higher data rate on each subcarrier, but because we are sending the same data stream on each subcarrier, it is still possible to reliably recover the original data stream at the receiver.



DFT = discrete Fourier transform
IDFT = inverse discrete Fourier transform
FFT = fast Fourier transform
IFFT = inverse fast Fourier transform
EQ = subcarrier equalization
CP = cyclic prefix

Figure 8.8 Simplified Block Diagram of OFDMA and SC-FDMA



(a) OFDMA: Data symbols occupy f_b kHz for one OFDMA symbol period

(b) SC-FDMA: Data symbols occupy $N \times f_b$ kHz for 1/N SC-FDMA symbol period

Figure 8.9 Example of OFDMA and SC-FDMA

A final observation concerns the term *multiple access*. With OFDMA, it is possible to simultaneously transmit either from or to different users by allocating the subcarriers during any one time interval to multiple users. This is not possible with SC-FDMA: At any given point in time, all of the subcarriers are carrying the identical data stream and hence must be dedicated to one user. But over time, as illustrated in Figure 8.9, it is possible to provide multiple access. Thus, a better term for SC-FDMA might be SC-OFDM-TDMA, although that term is not used.

8.4 RECOMMENDED READING

[BERA08] and [MYUN06] provide good treatment of OFDMA and SC-FDMA. [GHOS11] provides discussion of OFDMA and LTE.

BERA08 Beradinelli, G., et al. "OFDMA vs SC-FDMA: Performance Comparison in Local Area IMT-A Scenarios." *IEEE Wireless Communications,* October 2008.

GHOS11 Ghosh, A.; Zhang, J.; Andrews J.; and Muhamed, R. *Fundamentals of LTE.* Upper Saddle River, NJ: Prentice Hall, 2011.

MOLI11 Molisch, A, *Wireless Communications,* Second Edition, West Sussex, UK: John Wiley & Sons, Ltd.

MYUN06 Myung, H.; Lim, J.; and Goodman, D. "Single Carrier FDMA for Uplink Wireless Transmission." *IEEE Vehicular Technology,* September 2006.

8.5 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

cyclic prefix	opportunistic scheduling	peak-to-average power ratio (PAPR)
discrete Fourier transform (DFT)	orthogonality	proportional fairness
fast Fourier transform (FFT)	orthogonal frequency division multiplexing (OFDM)	single-carrier FDMA (SC-FDMA)
intercarrier interference (ICI)	orthogonal frequency division multiple access (OFDMA)	
inverse fast Fourier transform (IFFT)		

Review Questions

8.1 Briefly define OFDM, OFDMA, and SC-FDMA.

8.2 What is the fundamental requirement of OFDM?

8.3 What are the main strengths of OFDM?

8.4 What are the main technical problem issues of OFDM?

8.5 What are the main differences between OFDM and OFDMA?

8.6 How does the IFFT approach affect the number of oscillators required in the transmitter? In the receiver?

8.7 How does orthogonality allow for increased capacity?

8.8 What problem does the cyclic prefix address?

8.9 OFDM creates several lower-rate (i.e., longer symbol time) subcarriers. Why is that helpful?

8.10 What are the benefits of each of the following OFDMA approaches – adjacent subcarriers, regularly spaced subcarriers, and randomly spaced subcarriers?

8.11 What is the purpose of using SC-FDMA?

Problems

8.1 For an 18 Mbps LTE data stream with a symbol time of 66.67 μs, how many subcarriers are created?

8.2 LTE assigns subcarriers in *resource blocks* of 180 kHz. Given the information in Problem 8.1, how many subcarriers are in a resource block? Approximate $B_S \approx r_b$.

8.3 Now consider a different system than described in Problems 8.1 and 8.2. Recall from Chapter 6 that a system is considered *flat fading* if the coherence bandwidth B_C is much, much greater (using a factor of 10) than the signal bandwidth B_S. A channel is found to have a coherence bandwidth of 80 kHz and to be frequency selective for a high data rate signal of 16 Mbps. How many subcarriers are needed to make each subcarrier a flat fading signal? Approximate $B_S \approx r_b$.

8.4 The cyclic prefix is intended to be long enough to encompass most significant multipath signals. Consider one of the LTE CP durations of 4.7 μs. Multipath delays come from signals traveling longer distances that the shortest path signal. If the shortest path between TX and RX is 1 km, what is the distance of the longest traveled multipath signal if the multipath delay should be much, much less (again using a factor of 10) than the CP duration? Assume signals travel at the speed of light.

8.5 Find the relationship between subcarrier frequencies f_1 and f_2 that is required for two subcarriers to be orthogonal to satisfy the following orthogonality condition. Assume f_1 and f_2 are both integer multiples of $\frac{1}{T_b}$.

$$\int_0^{T_b} \cos(2\pi f_1 t)\cos(2\pi f_2 t)\,dt = 0$$

8.6 For Problem 8.5, what is the minimum spacing that is possible to still maintain orthogonality?