Chapter 3
Choice of Multiple Access Technique

Abstract Multiple access techniques enable many users to share the same spectrum in the frequency domain, time domain, code domain, or phase domain. These techniques are readily available as international standards and can be used to provide cellular services in a given geographical area. This chapter presents a brief overview of the various multiple access techniques available today. Numerous illustrations are used to bring students up-to-date in key concepts, underlying principles and practical applications of FDMA, TDMA, CDMA, and OFDMA. The mode of operation such as fDD and TDD is also presented with illustrations. To illustrate the concept, we present the construction of these radios.

3.1 Introduction to Multiple Access Techniques

The multiple access technique is well known in cellular communications [1–6]. It enables many users to share the same spectrum in the frequency domain, time domain, code domain, or phase domain. It begins with a frequency band, allocated by the FCC (Federal Communication Commission) [7]. The FCC provides licenses to operate wireless communication systems over given bands of frequencies. These bands of frequencies are finite and have to be further divided into smaller bands (channels) and reused to provide services to other users. This is governed by the International Telecommunication Union (ITU) [8]. ITU generates standards such as FDMA, TDMA, CDMA, OFDMA, etc., for wireless communications. Figure 3.1 illustrates the basic concept of various multiple access techniques currently in use.

In any multiple access technique, multiple users have access to the same spectrum, so that the occupied bandwidth does not exceed the FCC-allocated channel. Furthermore, as the size and speed of digital data networks continue to expand, bandwidth efficiency becomes increasingly important. This is especially true for broadband communication, where the choice of modulation scheme is important keeping in mind the available bandwidth resources, allocated by FCC.

With these constraints in mind, this chapter will present a comprehensive yet concise overview of multiple access techniques used in the cellular industry.

S. Faruque, *Radio Frequency Cell Site Engineering Made Easy*, SpringerBriefs in Electrical and Computer Engineering, https://doi.org/10.1007/978-3-319-99615-8_3

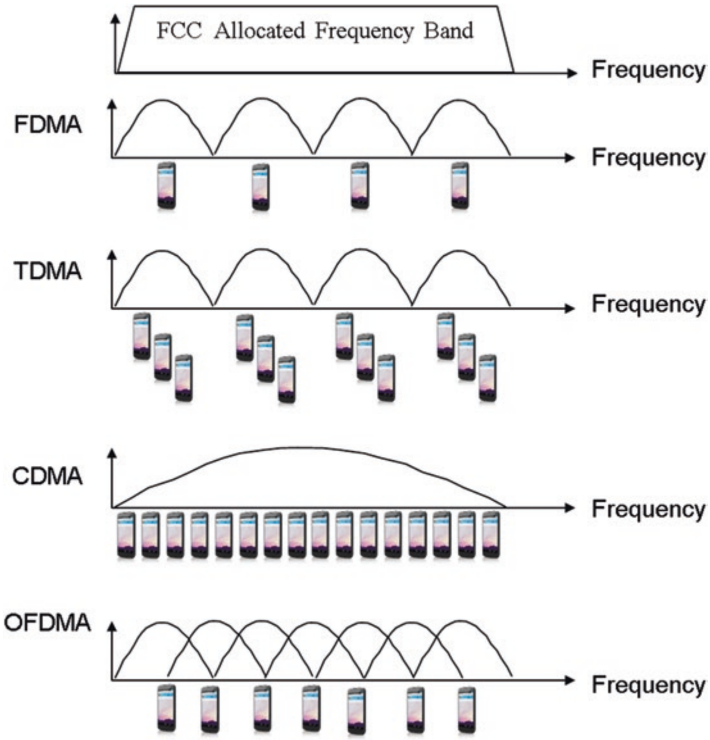


Fig. 3.1 Basic concept of multiple access techniques

3.2 Frequency Division Multiple Access (FDMA)

3.2.1 FDMA Concept

FDMA (Frequency Division Multiple Access) is the oldest communication technique, used in broadcasting, land-mobile two-way radio, etc. [1]. It begins with a band of frequencies, allocated by the FCC (Federal Communications Commission). The FCC provides licenses to operate wireless communication systems over given bands of frequencies. These bands of frequencies are further divided into several channels and assigned to users for full-duplex communication. Figure 3.2 illustrates the basic principle of a typical FDMA technique.

As shown in the figure, the FCC-allocated frequency band is divided into several frequencies, also known as channels. Each channel is assigned to a single user. In this scheme, the channel is occupied for the entire duration of the call. The communication link is maintained in both directions, either in the frequency domain or in the time domain. This is governed by two basic mode of operations listed below:

- Frequency division duplex (FDD)
- Time division duplex (TDD)

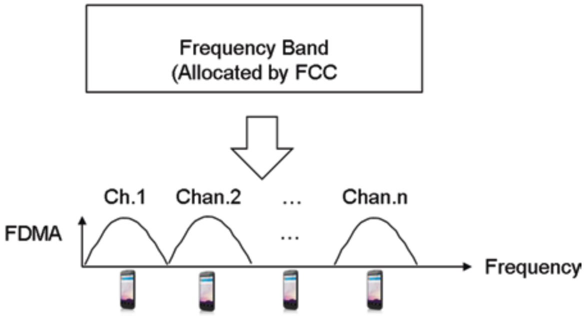


Fig. 3.2 Illustration of a typical FDMA technique. The FCC-allocated frequency band is divided into several channels. Each channel is assigned to a user

In FDD, all the available channels are divided into two bands, lower band and upper band, and grouped as pairs, one for the upload and the other for the download, separated by a guard band. As a result, both transmissions can take place at the same time without interference. This scheme is known as FDMA-FDD technique.

In TDD, a single frequency is time-shared between the uplink and the downlink. In this scheme, when the mobile transmits, base station listens, and when the base station transmits, the mobile listens. This is accomplished by formatting the data into a "frame," where the frame is a collection of several time slots. Each time slot is a package of data, representing digitized voice, digitized text, digitized video, and synchronization bits (sync bits). The sync bits are unique, which is used for frame synchronization. This scheme is known as FDMA-FDD technique.

3.2.2 FDMA-FDD Technique

In FDMA-FDD, all the available channels are divided into two bands, lower band and upper band, and grouped as pairs—L1U1, L2U2, …, LnUn. This is shown in Fig. 3.3. As can be seen in the figure, FDD uses two different frequencies, one for the upload and the other for the download, separated by a guard band. As a result, both transmissions can take place at the same time without interference. This scheme is known as FDMA-FDD technique.

A brief description of FDMA-FDD communication, as implemented in 1G cellular system [1–3], is presented below:

- The base station modulates the carrier frequency (U1) from the upper band and sends the modulated carrier to the mobile. The input modulating signal can be either analog or digital.
- Since the mobile is tuned to the same carrier frequency, it receives the modulated carrier from the base after a propagation delay. It then demodulates the carrier and recovers the information signal.
- In response, the mobile modulates a different carrier frequency (L1) from the lower band and transmits back to the base.
- The base station receives the modulated signal from the mobile and demodulates and recovers the information.
- The process continues until one of the transmitter terminates the call.

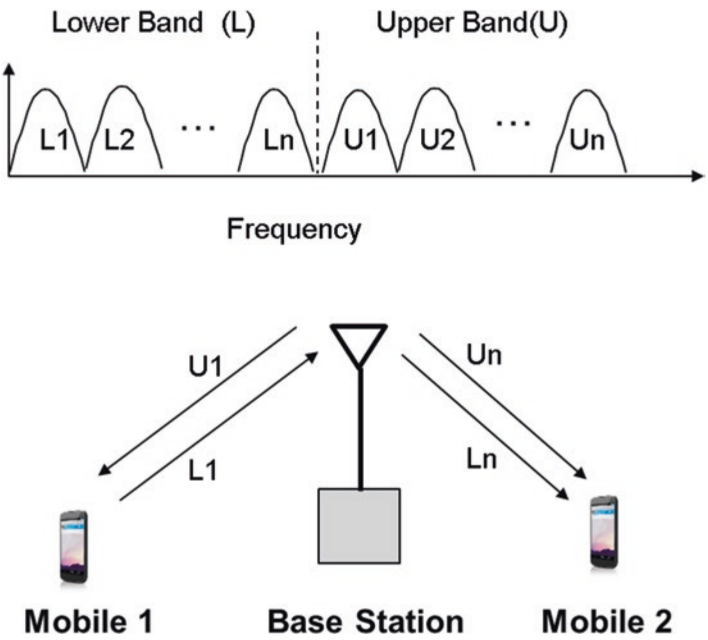


Fig. 3.3 Frequency division duplex (FDD) technique. Both frequencies can operate at the same time without interference

3.2.3 FDMA-TDD Technique

In FDMA-TDD, a single FDMA frequency is time-shared between the uplink and the downlink. The duration of transmission in each direction is generally short, in the order of ms. In this scheme, when the mobile transmits, base station listens, and when the base station transmits, the mobile listens. This is accomplished by formatting the data into a "frame," where the frame is a collection of several time slots. Each time slot is a package of data, representing digitized voice, digitized text, digitized video, and synchronization bits (sync bits). The sync bits are unique, which is used for frame synchronization. Figure 3.4 illustrates a typical frame and the TDD transmission scheme.

According to TDD transmission, both the base station and the mobile use the same carrier frequency. The transmit/receive mechanism between the base station and mobile is as follows:

- The base station modulates the carrier frequency by means of the digital information bits in frame F(B) and transmits to the mobile.
- Since the mobile is tuned to the same carrier frequency, it receives the frame F(B) after a propagation delay t_p.
- The mobile synchronizes the frame using the sync bits and downloads the data.

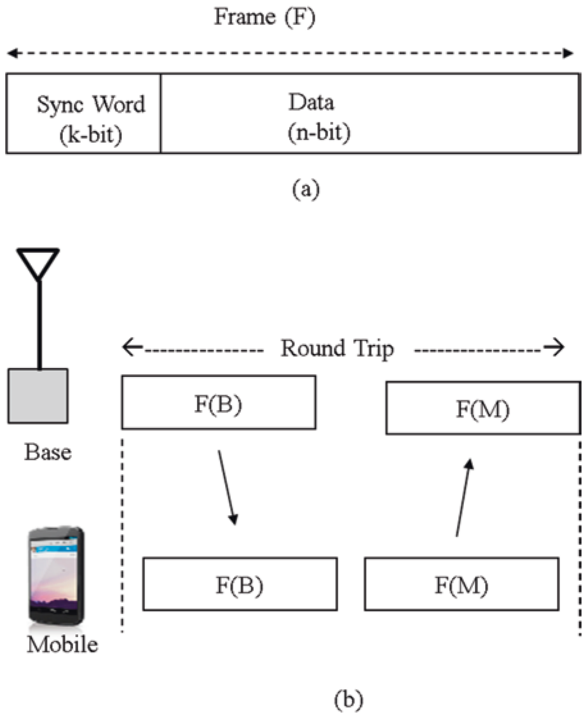


Fig. 3.4 TDD frame structure. (**a**) Frame. (**b**) Frame transmission scheme

- After a guard time t_g, mobile transmits its own frame F(M) to the base using the same carrier frequency.
- Base receives the frame from the mobile after a propagation delay t_p, maintains sync using the sync bits, and downloads the data.
- The round trip communication is now complete.
- The communication continues until one terminates the call.

As can be seen in the figure, the TDD schemes require a propagation delay and a guard time between transmission and reception. The complete round trip delay T_d must be sufficient to accommodate the frame, propagation delay, and the guard time. Therefore, the round trip delay can be written as:

$$T_d = 2\left(F + t_p + t_g\right) \tag{3.1}$$

The round trip delay T_d depends on the frame length F, which is generally in milliseconds (ms). The propagation delay t_p depends on the propagation distance, and the guard time t_g depends on the technology.

In 4G cellular communications, such as OFDMA and LTE, the traffic in both directions is not balanced. The volume of data transmission can be dynamically adjusted in each direction by means of the TDD technique. There is scheduling protocol, which can be dynamically controlled to offer high-speed data over the downlink and low-speed data over the uplink. This is accomplished by transmitting more time slots over the downlink, thereby supporting more capacity. For these reasons, TDD is used in 4G cellular system as WiMAX and LTE standards [4, 5].

3.3 Time-Division Multiple Access (TDMA)

3.3.1 TDMA Concept

TDMA (time-division multiple access) for wireless communication is an extension of FDMA, where each FDMA channel is time-shared by multiple users, one at a time [2]. It begins with a band of frequencies, which is allocated by the FCC (Federal Communications Commission). This band of frequencies further divided into several narrow bands of frequencies, where each frequency, also known as channel, is used for full-duplex communication by multiple users one at a time as depicted in Fig. 3.5.

Figure 3.6 illustrates the basic concept of a full-duplex cellular communication system, developed as the second-generation (2G) cellular communication system, based on TDMA-FDD technique [1–5]. In this technique, a pair of FDMA channels is used during a call, one from the lower band and one from the upper band. The lower band frequency is time-shared by several mobiles. The upper band frequency is also time-shared synchronously by the base station radio. Both channels are occupied during the entire duration of the call.

Synchronization is achieved by means of a special frame structure, where the frame is a collection of time slots. Each time slot is assigned to a mobile. This implies that when one mobile has access to the channel, the other mobiles are idle. Therefore, TDMA synchronization is critical for data recovery and collision avoidance.

TDMA has several advantages over FDMA:

- Increased channel capacity
- Greater immunity to noise and interference
- Secure communication
- More flexibility and control

Moreover, it allows the existing FDMA standard to coexist in the same TDMA platform, sharing the same RF spectrum.

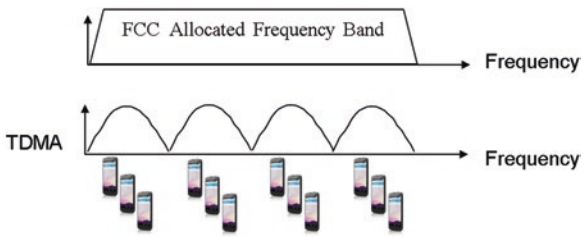


Fig. 3.5 North American cellular TDMA technique. The FCC-allocated frequency band is divided into several channels where each channel is time-shared by several users one at a time

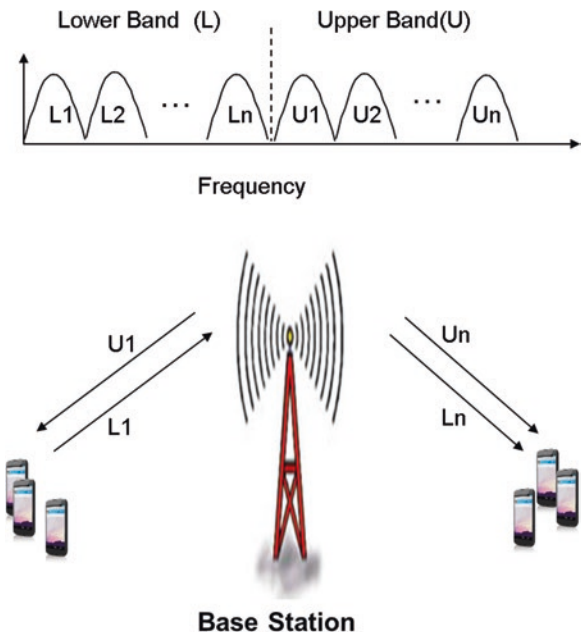


Fig. 3.6 North American 2G cellular TDMA communication system

3.3.2 TDMA Frame Structure

The North American 2G TDMA air link is based on a 40 ms frame structure, equally divided into six time slots, 6.667 ms each. Each of the six time slots contains 324 gross bit intervals, corresponding to 162 symbols (π/4 DQPSK modulation, 1 symbol = 2 bits of information). Figure 3.7 shows the forward link (base to mobile) TDMA frame structure. In TDMA-3, the time slots are paired as 1–4, 2–5, and 3–6 where each disjointed pair of time slots is assigned to a mobile. This arrangement enables three mobiles to access the same 30 kHz channel one at a time.

The TDMA-3 forward link uses a rate 1/2 convolutional encoding with interleaving. The encoded 48.6 kb/s data bit stream is modulated by means of a π/4 DQPSK modulation and then transmitted from the base station to the mobile where each mobile receives data at 16.2 kb/s. At the receive side, the RF signal is demodulated and decoded, and finally the original data is recovered. Since this is a radio channel, the recovered data is impaired by noise, interference, and fading. As a result, the information is subject to degradation. Although error control coding greatly enhances the performance, the C/I (carrier-to-interference ratio) is still the limiting factor. The TDMA-3 reverse link is exactly the reverse process.

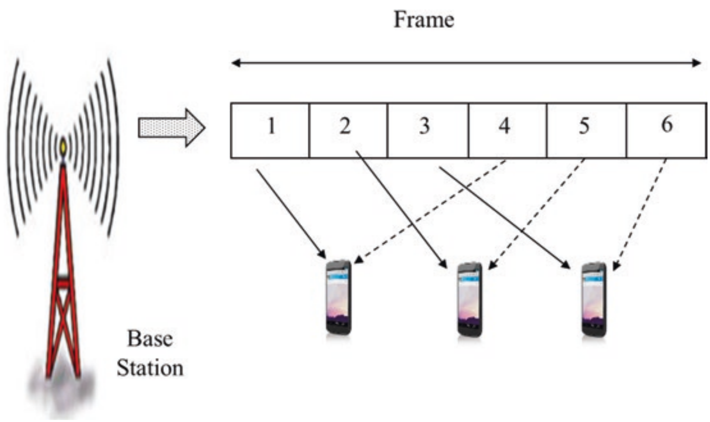
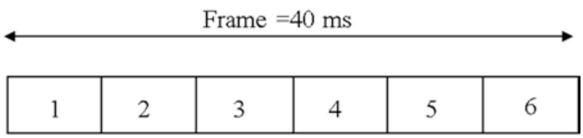


Fig. 3.7 TDMA forward link format

Problem
Given:

- Frame length = 40 ms (figure below).
- The frame contains six time slots and supports three users.
- Each user originates 16.2 kb/s data.



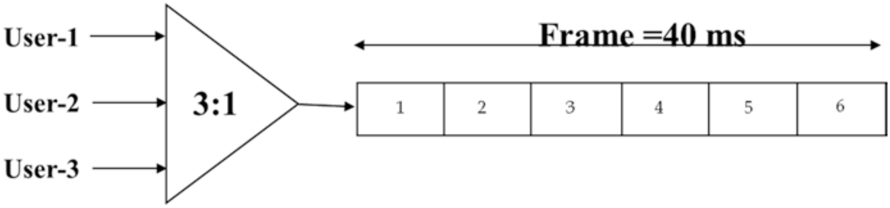
Find:

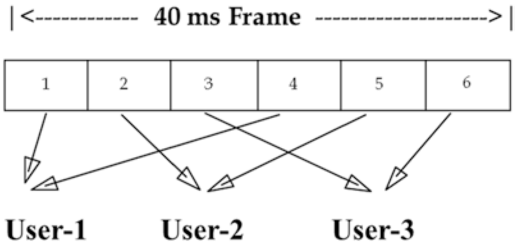
(a) A suitable multiplexing structure
(b) The composite data rate in the channel
(c) Number of bits/frame

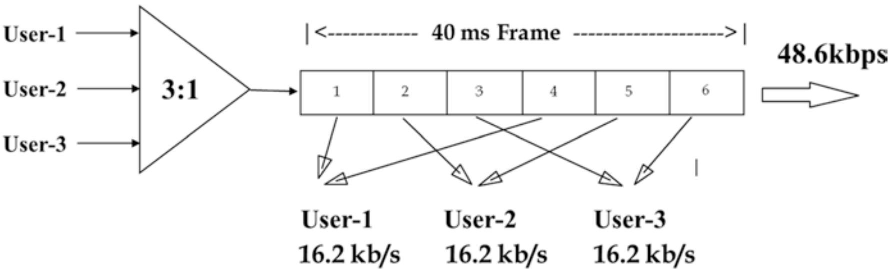
Solution:

(a) We have three users and six time slots. Therefore, we can assign two time slots/user:

- User 1: Time slots 1 and 4
- User 2: Time slots 2 and 5
- User 3: Time slots 3 and 6







(b) Composite data rate: 16.2 kb/s/user × 3 = 48.6 kb/s

(c) Number of bits/frame = frame length/bit duration = 40 ms/(1/48.6 kb/s) = 1944 bits/frame

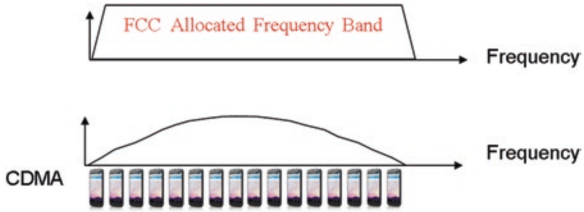
3.4 Code-Division Multiple Access (CDMA)

3.4.1 CDMA Concept

CDMA (code-division multiple access) is a spread spectrum (SS) communication system where multiple users have access to the same career frequency at the same time [3]. It begins with a frequency band, allocated by the Federal Communication Commission (FCC) as shown in Fig. 3.8. The FCC provides licenses to operate wireless communication systems over given bands of frequencies. These frequency bands are finite and have to be reused to support a large number of users in a given geographical area.

The objective of this chapter is to review spectrum, spectrum spreading, and de-spreading techniques and show how it relates to spread spectrum CDMA radio.

Fig. 3.8 FCC-allocated frequency band and its use in CDMA as spread spectrum. Multiple users have access to the same frequency at the same time



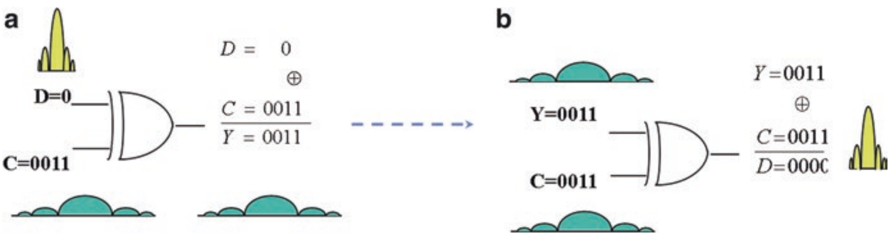


Fig. 3.9 Spreading and de-spreading technique. (**a**) Spreading bit 0. (**b**) De-spreading and recovering bit 0

3.4.2 Spectrum Spreading and De-spreading

In CDMA, each user is assigned a unique n-bit orthogonal code as a user ID, spectrum spreading at the transmit side, and de-spreading at the receive side. Spectrum spreading is accomplished by multiplying each NRZ data bit by means of an n-bit orthogonal code. Multiplication in this process is referred to as exclusive OR (EXOR) operation. The output of the EXOR (exclusive OR gate) is now a high-speed orthogonal or antipodal code. De-spreading is a similar process, where the receiver multiplies the incoming data by means of the same orthogonal code and recovers the data. Let us examine these operations using a 4-bit orthogonal code, where the code sequence is given by 0011 and the input NRZ data is 0 and 1.

Example 1: Spreading Bit 0 and De-spreading to Recover Bit 0 This is shown in Fig. 3.9. When the binary bit 0 is multiplied by a 4-bit orthogonal code 0011, we write:

$$0 \text{ EXOR } (0011) = 0011 \tag{3.2}$$

This is the orthogonal code, reproduced due to exclusive OR operation. Moreover, the bit rate is also multiplied by a factor of 4, thereby spreading the spectrum by a factor of 4 as well. This is the wide band data which is transmitted to the receiver. Upon receiving 0011, the receiver performs the de-spreading function using the same orthogonal code 0011, which is also an EXOR function. Thus we write:

$$0011 \text{ EXOR } 0011 = 0000$$

This is the original data bit 0, which has been reproduced due to exclusive OR operation. Moreover, the bit rate is also divided by a factor of 4.

Example 2: Spreading Bit 1 and De-spreading to Recover Bit 1 This is shown in Fig. 3.10. When the binary bit 1 is multiplied by the same orthogonal code, we obtain:

$$1 \text{ EXOR } (0011) = 1100 \tag{3.3}$$

This is the inverse of the orthogonal code. This code is also known as antipodal code. The spectrum is also spread by a factor of 4.

Upon receiving the antipodal code 1100, the receiver performs the de-spreading function using the same orthogonal code 0011, which is also an EXOR function. Thus we write 1100 EXOR 0011 = 1111. This represents the original data bit 1, which has been reproduced due to exclusive OR operation. Moreover, the bit rate is also divided by a factor of 4.

3.4.3 Construction of CDMA Radio

Let us examine a CDMA radio based on 4-bit orthogonal code, where the code sequence is given by 0101. This is shown in Figs. 3.11 and 3.12.

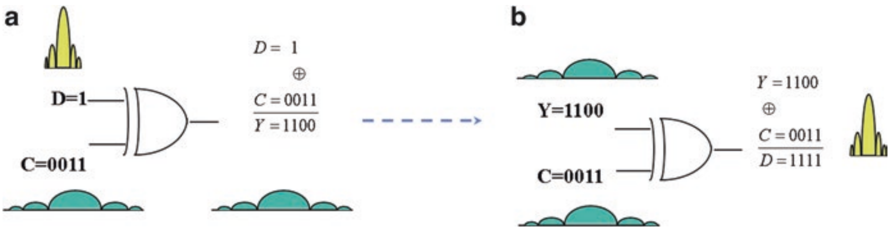


Fig. 3.10 Spreading and de-spreading technique. (**a**) Spreading bit 1. (**b**) De-spreading and recovering bit 1

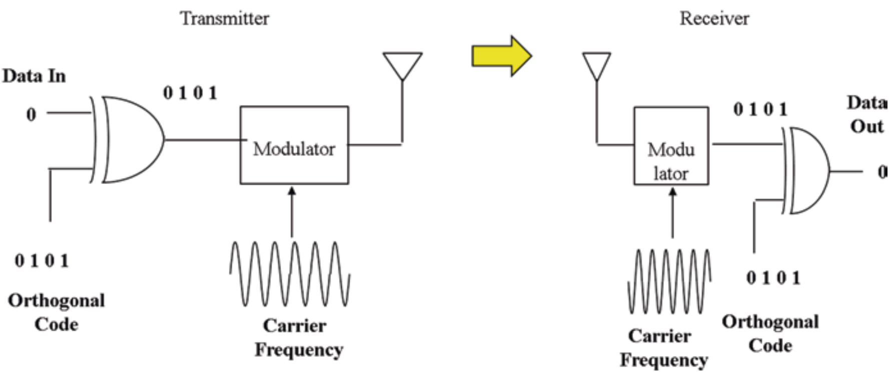


Fig. 3.11 CDMA radio. Binary bit 0 transmit/receive mechanism

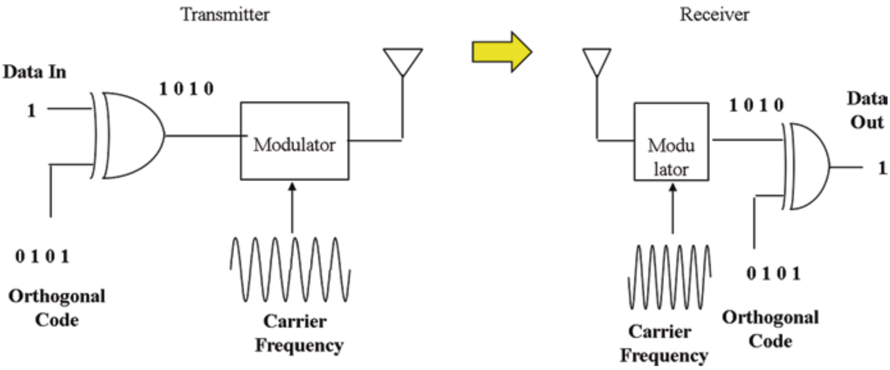


Fig. 3.12 CDMA radio. Binary bit 1 transmit/receive mechanism

In Fig. 3.11, the binary bit 0 is multiplied by the 4-bit orthogonal code to reproduce the orthogonal code as follows:

$$\left(\quad\right)\text{EXOR }\left(0101\right)=0101 \tag{3.4}$$

This represents the information bit 0, which is modulated and transmitted to the receiver.

The receiver intercepts the modulated carrier frequency and demodulates and recovers the orthogonal code 0101. Since the exclusive OR gate also uses the same orthogonal code, we obtain:

$$0101\text{ EXOR }\left(0101\right)=0000$$

This represents the original binary value 0.

Similarly, in Fig. 3.12, the binary bit 1 is multiplied by the same 4-bit orthogonal code to produce the antipodal code as follows:

$$1\text{ EXOR }\left(0101\right)=1010 \tag{3.6}$$

This represents the information bit 1, which is modulated and transmitted to the receiver. The receiver intercepts the modulated carrier frequency and demodulates and recovers the antipodal code 1010. Since the exclusive OR gate uses the same orthogonal code, we obtain:

$$1010\text{ EXOR }\left(0101\right)=1111$$

This represents the original binary value 1.

In summary, CDMA is a branch of multiple access techniques, where multiple users have access to the same spectrum through orthogonal codes. Orthogonal codes are binary valued and have equal number of 1s and 0s. Therefore, for an n-bit orthogonal code, there are n orthogonal codes. In CDMA, each user is assigned a unique orthogonal code. As a result, each user remains in orthogonal space after modulation and offers maximum isolation. Yet, there is a limit to the use of all the codes, which is related to channel capacity.

3.5 Orthogonal Frequency-Division Multiple Access (OFDMA)

3.5.1 OFDMA Concept

OFDMA (orthogonal frequency-division multiple access) [4, 5] is a relatively new wireless communication standard used in 4G-WiMAX (Worldwide Interoperability for Microwave Access) and 4G-LTE (long-term evolution) protocol. It may be noted that WiMAX is an IEEE 802.16 standard while LTE is a standard developed by the 3GPP group. Both standards are surprisingly similar and bandwidth efficient. OFDMA is used in the 4G cellular standard.

In OFDMA, each frequency is placed at the null of the adjacent frequency (see Fig. 3.13). This is governed by the well-known "Fourier transform," so that adjacent frequencies are orthogonal to each other. It begins with a band of frequencies. This band of frequencies is allocated by the FCC (Federal Communications Commission). This band of frequencies is further divided into several narrow bands of frequencies, where each frequency is orthogonal to each other. OFDMA is a full-duplex communication system. The communication link is maintained in both directions in the time domain known as time-division duplex (TDD).

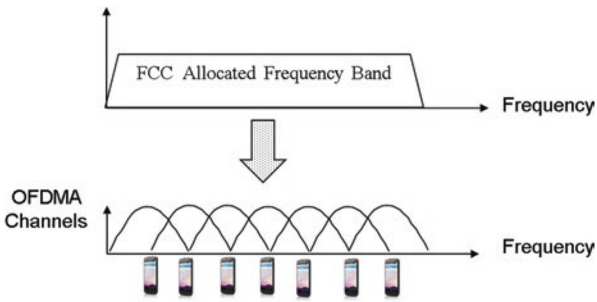


Fig. 3.13 Construction of OFDMA channels from FCC-allocated frequency band. There are n − 1 nulls in the FCC-allocated band, where n is the number of FDMA channels

3.5.2 OFDMA Radio and Spectrum Allocation

Figure 3.14 shows the basic OFDMA radio and spectrum allocation scheme. Here, each frequency band is placed at the null of the adjacent frequency band, where each frequency is orthogonal to each other. The adjacent bans are determined by the bit rate and modulation.

Since OFDMA is a full-duplex multiuser wireless communication system, a carrier frequency is assigned to a pair of users to operate in the TDD mode. In this scheme, the channel is occupied by two users for the entire duration of the call. The communication link is maintained in both directions in the time domain known as time-division duplex (TDD).

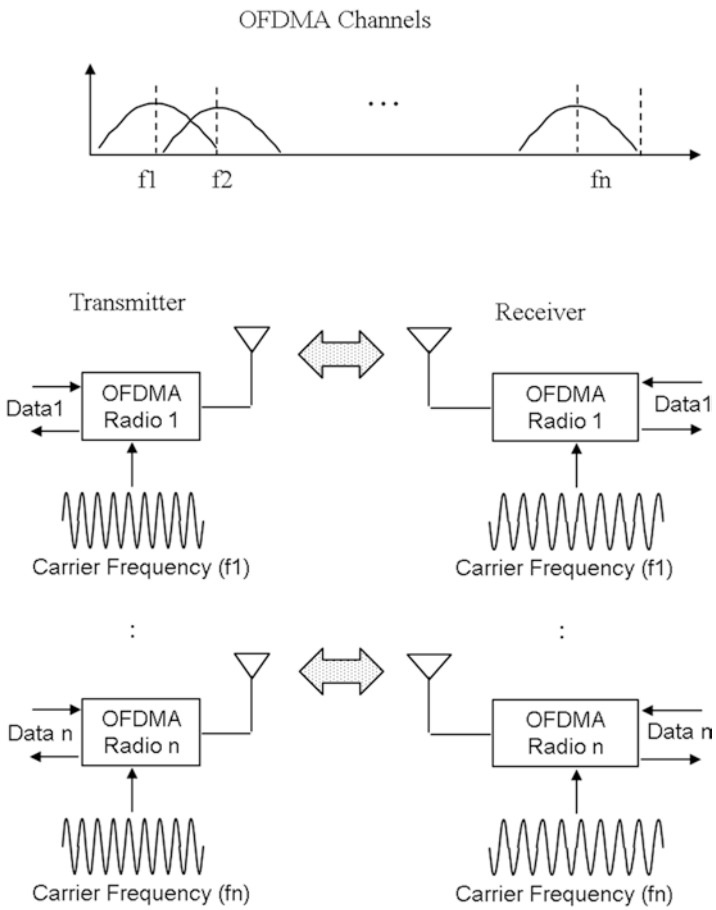


Fig. 3.14 OFDMA radio and spectrum allocation scheme. A single frequency is used in both directions. The mode of operation is TDD

3.5.3 OFDMA Channel Capacity

The bandwidth of each OFDMA channel is determined by the first null to first null of the two-sided response of the main lobe. Each frequency band is placed at the null of the adjacent band as shown in the figure. Notice that there are n − 1 nulls in the OFDMA spectrum, where n is the number of FDMA channels. Therefore, the number of OFDMA channels will be given by:

$$\text{Number of OFDMA Channels} = 2 \times \text{FDMA Channels} - 1 \tag{3.7}$$

3.5.4 OFDMA-TDD Mode of Operation

OFDMA is a full-duplex communication system. The communication link is maintained in both directions in the time domain known as time-division duplex (TDD). In OFDMA-TDD, a single frequency is time-shared between the uplink and the downlink. The duration of transmission in each direction is generally short, in the order of ms (millisecond). In this scheme, when the mobile transmits, base station listens, and when the base station transmits, mobile listens. This is accomplished by formatting the data into a "frame," where the frame is a collection of several time slots. Each time slot is a package of data, representing digitized voice, digitized text, digitized video, and synchronization bits (sync bits). These unique sync bits are used for synchronization.

Figure 3.15 illustrates a typical frame and the TDD transmission scheme. According to TDD transmission, both the base station and the mobile use the same carrier frequency. The transmit/receive mechanism between the base station and mobile is as follows:

- The base station modulates the carrier frequency by means of the digital information bits in frame F(B) and transmits to the mobile.
- Since the mobile is tuned to the same carrier frequency, it receives the frame F(B) after a propagation delay t_p.
- The mobile synchronizes the frame using the sync bits and downloads the data.
- After a guard time t_g, the mobile transmits its own frame F(M) to the base using the same carrier frequency.
- Base receives the frame from the mobile after a propagation delay t_p, maintains sync using the sync bits, and downloads the data.
- A round trip communication is now complete.
- The communication continues until one terminates the call.

As can be seen in the figure, the TDD schemes require a propagation delay and a guard time between transmission and reception. The complete round trip delay T_d must be sufficient to accommodate the frame, propagation delay, and the guard time. Therefore, the round trip delay can be written as:

$$T_d = 2\left(F + t_p + t_g\right) \tag{3.8}$$

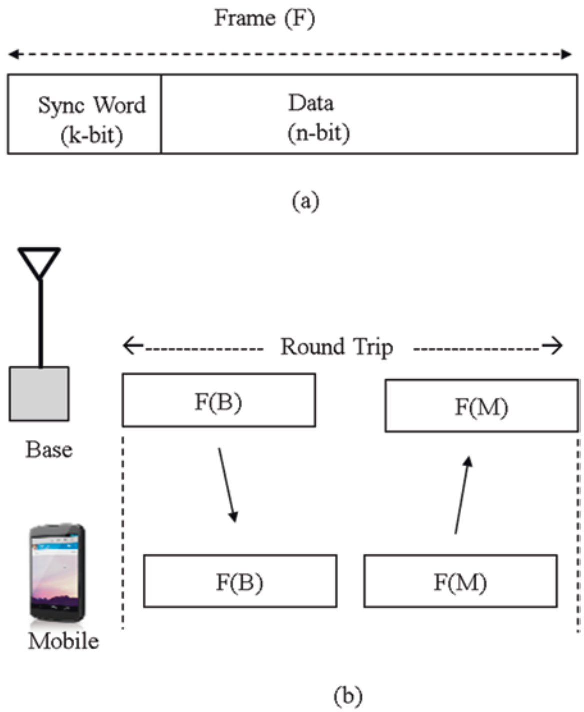


Fig. 3.15 OFDMA-TDD frame structure. (**a**) Frame. (**b**) Frame transmission scheme

The round trip delay T_d depends on the frame length F, which is generally in milliseconds (ms). The propagation delay t_p depends on the propagation distance, and the guard time t_g depends on the technology.

Problem

Given:

- Frame length = 2 ms
- Guard Time $t_g = 0.01$ ms
- Distance between the base station and mobile = 1 km
- Velocity of light $c = 3 \times 10^8$ m/s

Find:

- The round trip delay t_p.

Solution:

- Propagation delay for a distance of 1 km = 1 km/(3×10^8 m) = 3.3 ms
- Round trip delay $t_d = 2(t_p + t_f + t_g) = 2(3.3 \text{ ms} + 2 \text{ ms} + 0.01 \text{ ms}) = 5.31$ ms

3.6 Conclusions

Multiple access techniques enable many users to share the same spectrum in the frequency domain, time domain, code domain, or phase domain. It begins with a frequency band, allocated by FCC (Federal Communication Commission). FCC provides licenses to operate wireless communication systems over given bands of frequencies. These bands of frequencies are finite and have to be further divided into smaller bands (channels) and reused to provide services to other users. This is governed by the International Telecommunication Union (ITU). ITU generates standards such as FDMA, TDMA, CDMA, OFDMA, etc., for wireless communications. These standards are readily available and can be used to provide cellular services in a given geographical area.

This chapter presents a brief overview of various multiple access techniques used for cellular communications. Numerous illustrations are used to bring students up-to-date in key concepts, underlying principles, and practical applications of FDMA, TDMA, CDMA, and OFDMA. The mode of operation such as fDD and TDD is also presented with illustrations. Construction of these radios is also described for basic understanding.

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