

WIRELESS COMMUNICATION NETWORKS AND SYSTEMS

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more depth in Chapters 7 and 10. They essentially create signals that send as much information as possible for a given received signal strength and noise, then they detect and correct the errors. To adapt 100's of times per second, two features must be present in the protocols for a system.

1. Mechanisms to measure the quality of the wireless channel. These might include monitoring packet loss rates or sending special pilot signals expressly for measurement purposes.
2. Messaging mechanisms to communicate the signal quality indicators between transmitters and receivers, and also to communicate the new modulation and coding formats.

Bandwidth Expansion

All of the above correction mechanisms seek to increase the efficient use of the bandwidth of a channel, commonly measured in an efficiency of bps/Hz. But according to Shannon's theory there is a limit to this efficiency for a given signal to noise ratio. If throughput requirements are beyond what can be achieved in a given bandwidth, a series of bandwidth expansion approaches are used.

- **Carrier aggregation** combines multiple channels. For example, 802.11n and 802.11ac combine the 20 MHz channels from earlier 802.11 standards into 40, 80, or 160 MHz channels.
- **Frequency reuse** allows the same carrier frequencies to be reused when devices are sufficiently far enough away so the signal-to-interference ratio is low enough. This has traditionally been provided by breaking a cellular coverage area into large cells, called *macro cells*, of several kilometers in diameter. Cells far enough away can reuse the frequencies. But now **small cells** with limited power and range are being used for the same frequency reuse objectives. Indoor small cells are commonly called **femtocells** and outdoor cells are provided by *relays* or **picocells**. These are discussed in conjunction with LTE in Chapter 14. This approach is called **network densification** because it allows frequencies to be reused many times.
- **Millimeter wave (mmWave)** bands are higher frequencies in the 30 GHz to 300 GHz bands that have more bandwidth available in wider bandwidth channels. Recall that $\lambda = c/f$, so 30 to 300 GHz has wavelengths of 10 to 1 mm. This is an example of using different carrier frequencies to achieve higher bandwidth, given spectrum regulations. mmWave bands are more difficult to use, however, since they are more susceptible to attenuation by obstructions and **atmospheric absorption**. IEEE 802.11ad uses mmWave bands within a single room. Future technologies, however, may use them for wider range communication, in conjunction with higher gain MIMO configurations.

5.5 DIGITAL SIGNAL ENCODING TECHNIQUES

A variety of methods are used to encode analog and digital data onto analog and digital signals. Many of these techniques are examined in Chapter 7, which is dedicated to signal encoding topics. Here, we only discuss the encoding of digital data onto analog signals, since most of today's wireless communication is the transmission of digital data.

The basis for analog signals is a continuous constant-frequency signal known as the carrier signal. This is represented by a sinusoidal function as follows.

$$s(t) = A \cos(2\pi f_c t + \theta) \quad (5.7)$$

This signal has an amplitude, A , a frequency, f , and a phase, θ . The frequency, f_c , that is used here is called the carrier frequency. This is chosen to be compatible with the transmission medium being used. In the case of wireless communication, frequencies and signal powers must also be used as specified by regulatory agencies.

Data is transmitted using a carrier signal by modulation. Modulation is the process of encoding source data onto the carrier signal. All modulation techniques involve sending information by changing one or more of the three fundamental frequency domain parameters: amplitude, frequency, and phase. Accordingly, there are three basic encoding or modulation techniques for transforming digital data into analog signals, as illustrated in Figure 5.10: amplitude-shift keying (ASK),

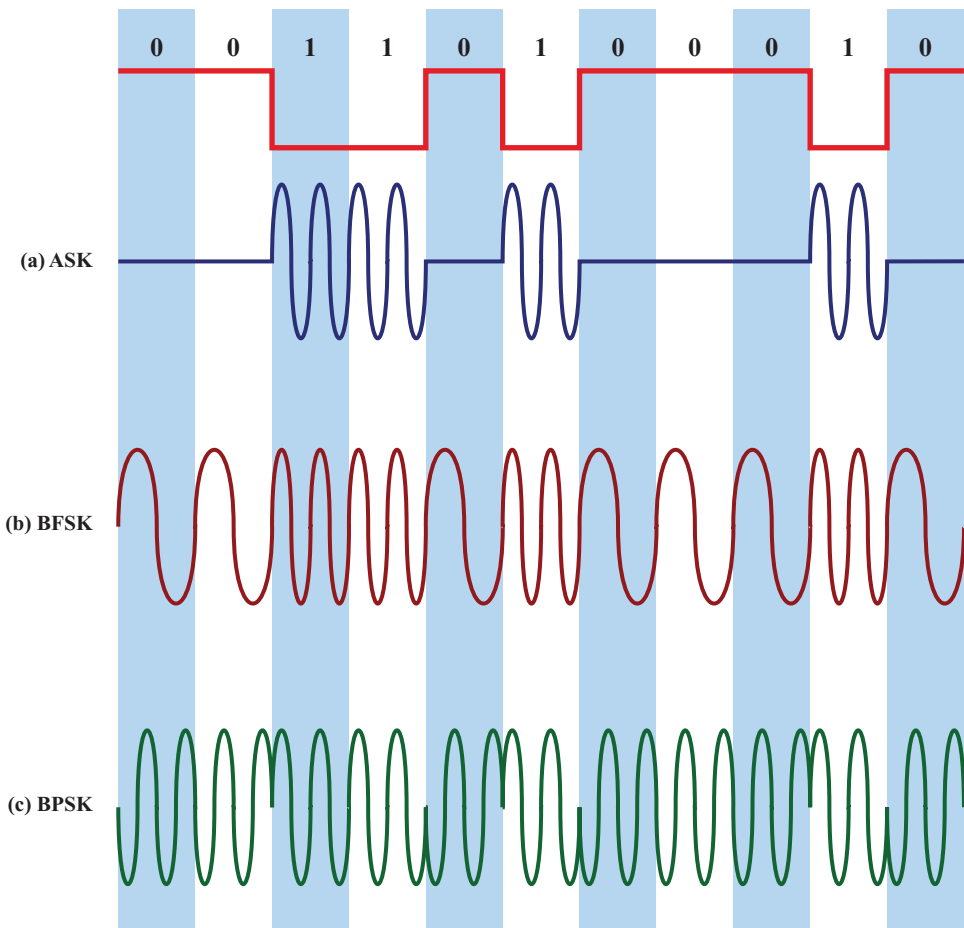


Figure 5.10 Modulation of Analog Signals for Digital Data



frequency-shift keying (FSK), and phase-shift keying (PSK). In all these cases, the resulting signal occupies a bandwidth centered on the carrier frequency.

- In **amplitude-shift keying (ASK)** the two binary values are represented by two different amplitudes of the carrier frequency. Commonly, one of the amplitudes is zero; that is, one binary digit is represented by the presence, at constant amplitude, of the carrier, the other by the absence of the carrier (Figure 5.10a).

$$\text{ASK} \quad s(t) = \begin{cases} A \cos(2\pi f_c t) & \text{binary 1} \\ 0 & \text{binary 0} \end{cases} \quad (5.8)$$

- The most common form of **frequency-shift keying (FSK)** is binary FSK (BFSK), in which the two binary values are represented by two different frequencies near the carrier frequency (Figure 5.10b).

$$\text{BFSK} \quad Bs(t) = \begin{cases} A \cos(2\pi f_1 t) & \text{binary 1} \\ A \cos(2\pi f_2 t) & \text{binary 0} \end{cases} \quad (5.9)$$

- In **phase-shift keying (PSK)**, the phase of the carrier signal is shifted to represent data. The simplest scheme uses two phases to represent the two binary digits (Figure 5.10c) and is known as binary phase-shift keying.

$$\text{BPSK} \quad s(t) = \begin{cases} A \cos(2\pi f_c t) \\ A \cos(2\pi f_c t + \pi) \end{cases} = \begin{cases} A \cos(2\pi f_c t) & \text{binary 1} \\ A \cos(2\pi f_c t) & \text{binary 0} \end{cases} \quad (5.10)$$

With two values of amplitude, frequency, or phase, one bit of information can be transmitted at a time. If, for example, four frequencies were used for FSK (which would then be called multilevel FSK or MFSK), two bits of information could be transmitted at a time. Each frequency could correspond to a two-bit sequence. This would effectively double the bit rate of the information transfer. If a scheme used M levels (M would always be a power of 2), the bit rate would increase by a factor of $L = \log_2(M)$ bits. If the same amount of transmitted power were still used, however, the bit error rate of the signal generally would also increase, creating a tradeoff between increased bit rates but also increased error rates.

Example 5.7 With $f_c = 250$ kHz and $M = 8$ ($L = 3$ bits), we can have the following frequency assignments for each of the 8 possible 3-bit data combinations if the frequencies are spaced apart by 50 kHz.

$$\begin{array}{llll} f_1 = 75 \text{ kHz } 000 & f_2 = 125 \text{ kHz } 001 & f_3 = 175 \text{ kHz } 010 & f_4 = 225 \text{ kHz } 011 \\ f_5 = 275 \text{ kHz } 100 & f_6 = 325 \text{ kHz } 101 & f_7 = 375 \text{ kHz } 110 & f_8 = 425 \text{ kHz } 111 \end{array}$$

When using a multilevel scheme, more than one of the signal characteristics can be changed. For example, 16-level Quadrature Amplitude Modulation (16QAM) uses various combinations of amplitudes and phases to create 16 different combinations. This would transmit four bits at a time. Figure 5.11 illustrates 16QAM in what is known as a constellation diagram. The amplitude of the signal will be the distance from the origin. For example, symbol 1111 would be transmitted with an amplitude of $\sqrt{1^2 + 1^2} = \sqrt{2}$. The phase of the signal would be the angle of the point in the