Pearson New International Edition

Wireless Communications and Networks

William Stallings

Second Edition

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Introduction to Wireless Communication

From Chapter 1 of *Wireless Communications and Networks*, Second Edition. William Stallings.

This text is a survey of the technology of wireless communications and networks. Many factors, including increased competition and the introduction of digital technology, have led to unprecedented growth in the wireless market. In this chapter, we discuss some of the key factors driving this new telecommunications revolution.

1 WIRELESS COMES OF AGE

Guglielmo Marconi invented the wireless telegraph in 1896.[1] In 1901, he sent telegraphic signals across the Atlantic Ocean from Cornwall to St. John's Newfoundland; a distance of about 3200 km. His invention allowed two parties to communicate by sending each other alphanumeric characters encoded in an analog signal. Over the last century, advances in wireless technologies have led to the radio, the television, the mobile telephone, and communications satellites. All types of information can now be sent to almost every corner of the world. Recently, a great deal of attention has been focused on satellite communications, wireless networking, and cellular technology.

Communications satellites were first launched in the 1960s. Those first satellites could only handle 240 voice circuits. Today, satellites carry about one-third of the voice traffic and all of the television signals between countries [EVAN98]. Modern satellites typically introduce a quarter-second propagation delay to the signals they handle. Newer satellites in lower orbits, with less inherent signal delay, have been deployed to provide data services such as Internet access.

Wireless networking is allowing businesses to develop WANs, MANs, and LANs without a cable plant. The IEEE has developed 802.11 as a standard for wireless LANs. The Bluetooth industry consortium is also working to provide a seamless wireless networking technology.

The cellular or mobile telephone is the modern equivalent of Marconi's wireless telegraph, offering two-party, two-way communication. The first-generation wireless phones used analog technology. These devices were heavy and coverage was patchy, but they successfully demonstrated the inherent convenience of mobile communications. The current generation of wireless devices is built using digital technology. Digital networks carry much more traffic and provide better reception and security than analog networks. In addition, digital technology has made possible value-added services such as caller identification. Newer wireless devices connect to the Internet using frequency ranges that support higher information rates.

The impact of wireless communications has been and will continue to be profound. Very few inventions have been able to "shrink" the world in such a manner. The standards that define how wireless communication devices interact are quickly

[1]The actual invention of radio communications more properly should be attributed to Nikola Tesla, who gave a public demonstration in 1893. Marconi's patents were overturned in favor of Tesla in 1943 [ENGE00].

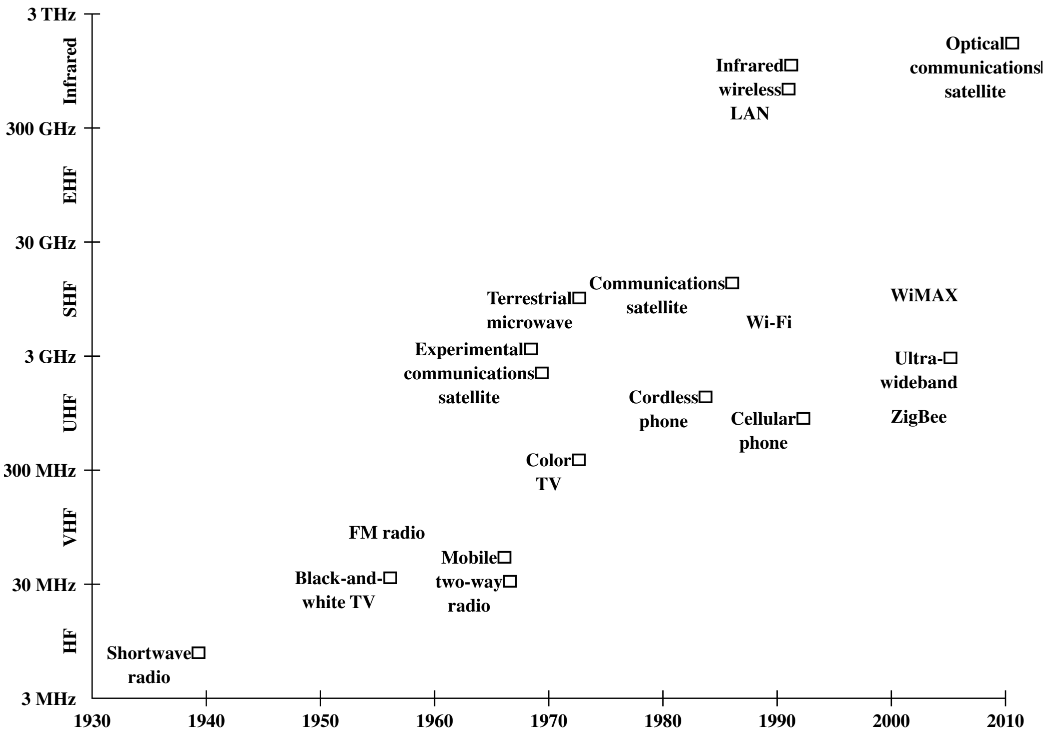

Figure 1 Some Milestones in Wireless Communications

converging and soon will allow the creation of a global wireless network that will deliver a wide variety of services.

Figure 1 highlights some of the key milestones in the development of wireless communications.[2] Wireless technologies have gradually migrated to higher frequencies. Higher frequencies enable the support of greater data rates and throughput.

2 THE CELLULAR REVOLUTION

The cellular revolution is apparent in the growth of the mobile phone market alone. In 1990, the number of users was approximately 11 million [ECON99]. Today, that number is in the billions. According to the ITU (International Telecommunications Union),[3] the number of mobile phones worldwide outnumbered fixed-line phones for the first time in 2002. The newer generation devices, with access to the Internet and built-in digital cameras, add to this momentum. There are a number of reasons

[2]Note the use of a log scale for the *y*-axis. A basic review of log scales is in the math refresher document at the Computer Science Student Resource Site at **WilliamStallings.com/StudentSupport.html.**

[3]A description of ITU and other standards-making bodies is contained in a supporting document at this text's Web site: **WilliamStallings.com/Wireless/Wireless2e.html**.

for the increasing dominance of mobile phones. Mobile phones are convenient; they move with people. In addition, by their nature, they are location aware. A mobile phone communicates with regional base stations that are at fixed locations.

Technical innovations have contributed to the success of mobile phones. The handsets have become smaller and lighter, battery life has increased, and digital technology has improved reception and allowed better use of a finite spectrum. As with many types of digital equipment, the costs associated with mobile telephones have been decreasing. In areas where competition flourishes, prices have dropped dramatically since 1996.

In many geographic areas, mobile telephones are the only economical way to provide phone service to the population. Operators can erect base stations quickly and inexpensively when compared with digging up ground to lay copper in harsh terrain.

Mobile telephones are only the tip of the cellular revolution. Increasingly, new types of wireless devices are being introduced. These new devices have access to the Internet. They include personal organizers and telephones, but now they have Web access, instant messaging, e-mail, and other services available on the Internet. Wireless devices in automobiles allow users to download maps and directions on demand. Soon, the devices may be able to call for help when an accident has occurred or perhaps notify the user of the lowest-priced fuel in the immediate area. Other conveniences will be available as well. For example, refrigerators may one day be able to order groceries over the Internet to replace consumed items.

The first rush to wireless was for voice. Now, the attention is on data. A big part of this market is the “wireless” Internet. Wireless users use the Internet differently than fixed users. Wireless devices have limited displays and input capabilities compared with typical fixed devices such as the PC. Transactions and messaging will be the rule instead of lengthy browsing sessions. Because wireless devices are location aware, information can be tailored to the geographic location of the user. Information will be able to find users, instead of users searching for information.

3 THE GLOBAL CELLULAR NETWORK

Today there is no single cellular network. Devices support one or two of a myriad of technologies and generally work only within the confines of a single operator’s network. To move beyond this model, more work must be done to define and implement standards.

The ITU is working to develop a family of standards for the next-generation wireless devices. The new standards will use higher frequencies to increase capacity. The new standards will also help overcome the incompatibilities introduced as the different first- and second-generation networks were developed and deployed over the last decade.

The dominant first-generation digital wireless network in North America was the Advanced Mobile Phone System (AMPS). This network offers a data service using the Cellular Digital Packet Data (CDPD) overlay network, which provides a 19.2-kbps data rate. The CPDP uses idle periods on regular voice channels to provide the data service.

The key second-generation wireless systems are the Global System for Mobile Communications (GSM), Personal Communications Service (PCS) IS-136, and PCS

IS-95. The PCS standard IS-136 uses time division multiple access (TDMA) while IS-95 uses code division multiple access (CDMA). The GSM and PCS IS-136 use dedicated channels at 9.6 kbps to deliver the data service.

The ITU is developing International Mobile Telecommunications-2000 (IMT-2000). This family of standards is intended to provide a seamless global network. The standards are being developed around the 2-GHz frequency band. The new standards and frequency band will provide data rates up to 2 Mbps.

In addition to defining frequency usage, encoding techniques, and transmission, standards also need to define how mobile devices will interact with the Internet. Several standards bodies and industry consortiums are working to that end. The Wireless Application Protocol (WAP) Forum is developing a common protocol that allows devices with limited display and input capabilities to access the Internet. The Internet Engineering Task Force (IETF) is developing a mobile IP standard that adapts the ubiquitous IP protocol to work within a mobile environment.

4 BROADBAND

The Internet is increasingly a multimedia experience. Graphics, video, and audio abound on the pages of the World Wide Web. Business communications are following the same trend. For example, e-mail frequently includes large multimedia attachments. In order to participate fully, wireless networks require the same high data rates as their fixed counterparts. The higher data rates are obtainable with broadband wireless technology.

Broadband wireless service shares the same advantages of all wireless services: convenience and reduced cost. Operators can deploy the service faster than a fixed service and without the cost of a cable plant. The service is also mobile and can be deployed almost anywhere.

There are many initiatives developing broadband wireless standards around many different applications. The standards cover everything from the wireless LAN to the small wireless home network. Data rates vary from 2 Mbps to well over 100 Mbps. Many of these technologies are available now and many more will become available in the next several years.

Wireless LANs (WLANs) provide network services where it is difficult or too expensive to deploy a fixed infrastructure. The primary WLAN standard is IEEE 802.11, which provides for data rates as high as 54 Mbps.

A potential problem with 802.11 is compatibility with Bluetooth. Bluetooth is a wireless networking specification that defines wireless communications between devices such as laptops, PDAs, and mobile phones. Bluetooth and some versions of 802.11 use the same frequency band. The technologies would most likely interfere with each other if deployed in the same device.

5 FUTURE TRENDS

Much of the development effort in new wireless technology makes use of portions of the frequency spectrum that do not, in many countries, require licensing. In the United States, two such frequency bands are Industrial, Scientific, and Medical

(ISM) band near 2.4 GHz and the newly allocated unlicensed radio band, the Unlicensed National Information Infrastructure (UNII) band. UNII was created by the FCC (Federal Communications Commission) to allow manufacturers to develop high-speed wireless networks. In order to find enough bandwidth to satisfy needs, the band was established at 5 GHz, making it incompatible with 2.4-GHz equipment. The free, unlicensed portions of the radio spectrum enable manufacturers to avoid billions of dollars in licensing fees.

For years, these radio frequencies were neglected, the lonely domain of cordless phones and microwave ovens. In recent years however, spurred by consumer demand and active standards bodies, considerable research and development is underway. The first significant fruit of this activity is **Wi-Fi** (Wireless Fidelity), the very popular wireless LAN technology based on the IEEE 802.11 standards. In essence, Wi-Fi refers to 802.11-compatible products that have been certified as interoperable by the Wi-Fi Alliance, a body specifically set up for this certification process. Wi-Fi covers not only office-based LANs, but also home-based LANs and publicly available *hot spots*, which are areas around a central antenna in which people can wirelessly share information or connect to the Internet with a properly equipped laptop.

Wi-Fi is just the first major step in utilizing these bands. Four other innovative technologies are working their way through the research, development, and standardization efforts: WiMAX, Mobile-Fi, ZigBee, and Ultrawideband. We survey these technologies briefly in this section.

WiMAX is similar to Wi-Fi. Both create hot spots, but while Wi-Fi can cover several hundred meters, WiMAX has a range of 40 to 50 km. Thus, WiMAX provides a wireless alternative to cable, DSL, and T1/E1 for last-mile broadband access. It will also be used as complimentary technology to connect 802.11 hot spots to the Internet. Initial deployments of WiMAX are in fixed locations, but a mobile version is under development. WiMAX is an interoperability specification based on IEEE 802.16.

Mobile-Fi is similar to the mobile version of WiMAX in terms of technology. The objective with Mobile-Fi is to provide Internet access to mobile users at data rates even higher than those available in today's home broadband links. In this context, mobile truly means mobile, not just movable. Thus, a Mobile-Fi user could enjoy broadband Internet access while traveling in a moving car or train. Mobile-Fi is based on the IEEE 802.20 specifications.

ZigBee functions at a relatively low data rate over relatively short distances, compared to Wi-Fi. The objective is to develop products that are very low cost, with low power consumption and low data rate. ZigBee technology enables the coordination of communication among thousands of tiny sensors, which can be scattered throughout offices, farms, or factories, picking up bits of information about temperature, chemicals, water, or motion. They're designed to use little energy because they'll be left in place for 5 or 10 years and their batteries need to last. ZigBee devices communicate efficiently, passing data over radio waves from one to the other like a bucket brigade. At the end of the line the data can be dropped into a computer for analysis or picked up by another wireless technology like Wi-Fi or WiMAX.

Ultrawideband serves a very different purpose than the other technologies mentioned in this section. Ultrawideband enables the movement of massive files at high data rates over short distances. For example, in the home, Ultrawideband would allow the user to transfer hours of video from a PC to a TV without any messy cords. On the road, a passenger who has a laptop in the trunk receiving data over Mobile-Fi could use Ultrawideband to pull that information up to a handheld computer in the front seat.

6 THE TROUBLE WITH WIRELESS

Wireless is convenient and often less expensive to deploy than fixed services, but wireless is not perfect. There are limitations, political and technical difficulties that may ultimately prevent wireless technologies from reaching their full potential. Two issues are incompatible standards and device limitations.

As mentioned previously, in North America there are two standards for digital cellular service. Internationally, there is at least one more. A device using PCS IS-136 will not work in an area where the deployed technology is PCS IS-95. Also mentioned previously is the inability to use Bluetooth and 802.11 in the same device. These are just two examples of problems that arise when industrywide standards do not exist. The lack of an industrywide standard holds the technologies back from delivering one of the true ideals of wireless: ubiquitous access to data.

Device limitations also restrict the free flow of data. The small display on a mobile telephone is inadequate for displaying more than a few lines of text. In addition, most mobile wireless devices cannot access the vast majority of WWW sites on the Internet. The browsers use a special language, wireless markup language (WML), instead of the de facto standard HTML.

Most likely, no one wireless device will be able to meet every need. The potential of wireless can be met but not with a single product. Wireless will succeed because it will be integrated into a variety of devices that can meet a variety of needs.

8 INTERNET AND WEB RESOURCES

There are a number of resources available on the Internet and the Web to support this text and to help one keep up with developments in this field.

Web Sites for This Text

A special Web page has been set up for this text at **WilliamStallings.com/Wireless/Wireless2e.html.** The site includes the following:

- **Useful Web sites:** There are links to other relevant Web sites, including the sites listed in this section.
- **Errata sheet:** An errata list for this text will be maintained and updated as needed. Please e-mail any errors that you spot to me. Errata sheets for my other books are at **WilliamStallings.com.**
- **Documents:** Includes a number of documents that expand on the treatment in the text. Topics include standards organizations and the TCP/IP checksum.
- **Figures:** All of the figures in this text in PDF (Adobe Acrobat) format.
- **Tables:** All of the tables in this text in PDF format.
- **Slides:** A set of PowerPoint slides, organized by chapter.
- **Internet mailing list:** The site includes sign-up information for the text's Internet mailing list.
- **Wireless courses:** There are links to home pages for courses based on this text; these pages may be useful to other instructors in providing ideas about how to structure their course.

I also maintain the Computer Science Student Resource Site, at **WilliamStallings.com/StudentSupport.html;** the purpose of this site is to provide documents, information, and useful links for computer science students and professionals. Links are organized into four categories:

- **Math:** Includes a basic math refresher, a queuing analysis primer, a number system primer, and links to numerous math sites
- **How-to:** Advice and guidance for solving homework problems, writing technical reports, and preparing technical presentations
- **Research resources:** Links to important collections of papers, technical reports, and bibliographies
- **Miscellaneous:** A variety of useful documents and links

Other Web Sites

There are numerous Web sites that provide information related to the topics of this text. Because the addresses for Web sites tend to change frequently, I have not included these in the text. For all of the Web sites listed in the text, the appropriate link can be found at this text's Web site.

The following Web sites are of general interest related to wireless communications:

- **Vendors:** Links to thousands of hardware and software vendors who currently have WWW sites, as well as a list of thousands of computer and networking companies in a Phone Directory
- **Wireless Developer Network:** News, tutorials, and discussions on wireless topics
- **Wireless.com:** An amazing list of links to all aspects or wireless communications, networking, and standards

USENET Newsgroups

A number of USENET newsgroups are devoted to some aspect of data communications or networking. As with virtually all USENET groups, there is a high noise-to-signal ratio, but it is worth experimenting to see if any meet your needs. The most relevant are

- **comp.std.wireless:** General discussion of wireless standards for wide area and local area networks. This is a moderated group, which keeps the discussion focused.
- **comp.dcom.*:** There are a number of data communications related newsgroups that begin with "comp.dcom."

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Transmission Fundamentals

From Chapter 2 of *Wireless Communications and Networks*, Second Edition. William Stallings.

TRANSMISSION FUNDAMENTALS

This chapter is self-contained for the reader with little or no background in data communications. For the reader with greater interest, references for further study are supplied at the end of the chapter.

1 SIGNALS FOR CONVEYING INFORMATION

In this text, we are concerned with electromagnetic signals used as a means to transmit information. An electromagnetic signal is a function of time, but it can also be expressed as a function of frequency; that is, the signal consists of components of different frequencies. It turns out that the frequency domain view of a signal is far more important to an understanding of data transmission than a time domain view. Both views are introduced here.

Time Domain Concepts

Viewed as a function of time, an electromagnetic signal can be either analog or digital. An **analog signal** is one in which the signal intensity varies in a smooth fashion over time. In other words, there are no breaks or discontinuities in the signal. A **digital signal** is one in which the signal intensity maintains a constant level for some period of time and then changes to another constant level.[1] Figure 1 shows

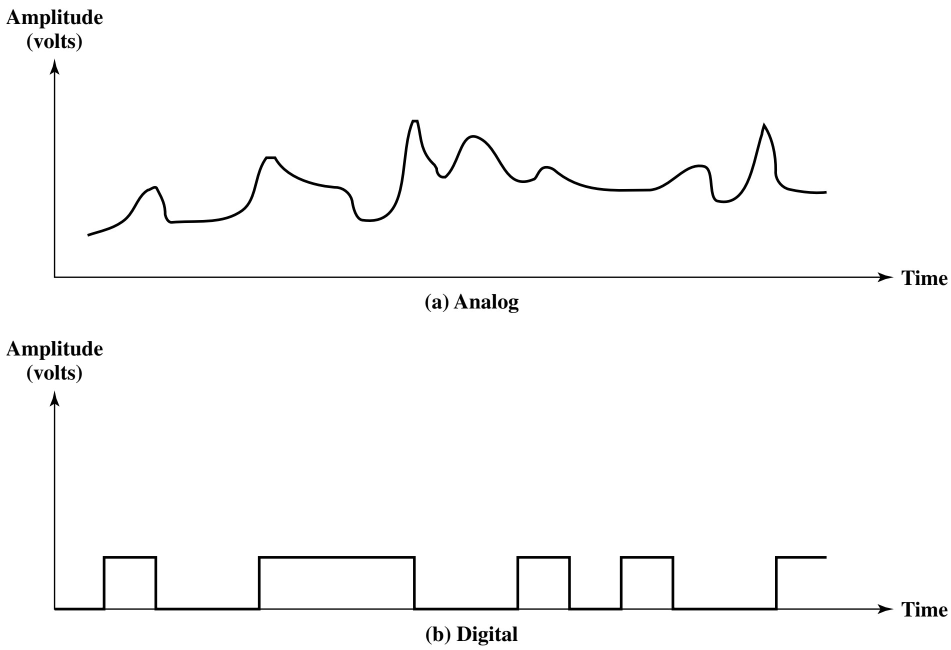

Figure 1 Analog and Digital Waveforms

[1]This is an idealized definition. In fact, the transition from one voltage level to another will not be instantaneous, but there will be a small transition period. Nevertheless, an actual digital signal approximates closely the ideal model of constant voltage levels with instantaneous transitions.

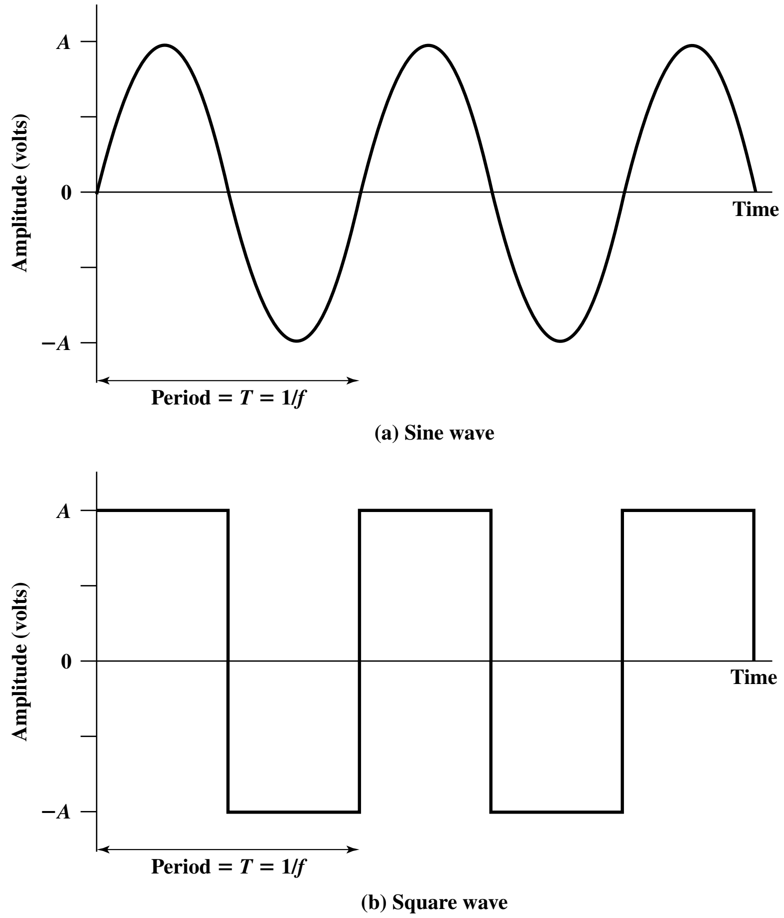

Figure 2 Examples of Periodic Signals

examples of both kinds of signals. The analog signal might represent speech, and the digital signal might represent binary 1s and 0s.

The simplest sort of signal is a **periodic signal**, in which the same signal pattern repeats over time. Figure 2 shows an example of a periodic analog signal (sine wave) and a periodic digital signal (square wave). Mathematically, a signal $s(t)$ is defined to be periodic if and only if

$$s(t + T) = s(t) \qquad -\infty < t < +\infty$$

where the constant T is the period of the signal (T is the smallest value that satisfies the equation). Otherwise, a signal is **aperiodic**.

The sine wave is the fundamental analog signal. A general sine wave can be represented by three parameters: peak amplitude (A), frequency (f), and phase (ϕ). The **peak amplitude** is the maximum value or strength of the signal over time; typically, this value is measured in volts. The **frequency** is the rate [in cycles per second, or Hertz (Hz)] at which the signal repeats. An equivalent parameter is the

period (T) of a signal, which is the amount of time it takes for one repetition; therefore, $T = 1/f$. **Phase** is a measure of the relative position in time within a single period of a signal, as illustrated later.

The general sine wave can be written

$$s(t) = A \sin(2\pi ft + \phi) \tag{1}$$

A function with the form of Equation (1) is known as a **sinusoid**. Figure 3 shows the effect of varying each of the three parameters. In part (a) of the figure, the frequency is 1 Hz; thus the period is $T = 1$ second. Part (b) has the same frequency and phase but a peak amplitude of 0.5. In part (c) we have $f = 2$, which is equivalent to $T = 1/2$. Finally, part (d) shows the effect of a phase shift of $\pi/4$ radians, which is 45 degrees (2π radians $= 360° = 1$ period).

In Figure 3 the horizontal axis is time; the graphs display the value of a signal at a given point in space as a function of time. These same graphs, with a change of scale, can apply with horizontal axes in space. In that case, the graphs display the value of a signal at a given point in time as a function of distance. For example, for a sinusoidal transmission (say, an electromagnetic radio wave some distance from a radio antenna or sound some distance from loudspeaker) at a particular instant of time, the intensity of the signal varies in a sinusoidal way as a function of distance from the source.

There is a simple relationship between the two sine waves, one in time and one in space. The **wavelength** (λ) of a signal is the distance occupied by a single cycle, or, put another way, the distance between two points of corresponding phase of two consecutive cycles. Assume that the signal is traveling with a velocity v. Then the wavelength is related to the period as follows: $\lambda = vT$. Equivalently, $\lambda f = v$. Of particular relevance to this discussion is the case where $v = c$, the speed of light in free space, which is approximately 3×10^8 m/s.

Frequency Domain Concepts

In practice, an electromagnetic signal will be made up of many frequencies. For example, the signal

$$s(t) = (4/\pi) \times (\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t))$$

is shown in Figure 4c. The components of this signal are just sine waves of frequencies f and $3f$; parts (a) and (b) of the figure show these individual components. There are two interesting points that can be made about this figure:

- The second frequency is an integer multiple of the first frequency. When all of the frequency components of a signal are integer multiples of one frequency, the latter frequency is referred to as the **fundamental frequency**.
- The period of the total signal is equal to the period of the fundamental frequency. The period of the component $\sin(2\pi ft)$ is $T = 1/f$, and the period of $s(t)$ is also T, as can be seen from Figure 4c.

It can be shown, using a discipline known as Fourier analysis, that any signal is made up of components at various frequencies, in which each component is a sinusoid. By adding together enough sinusoidal signals, each with the appropriate

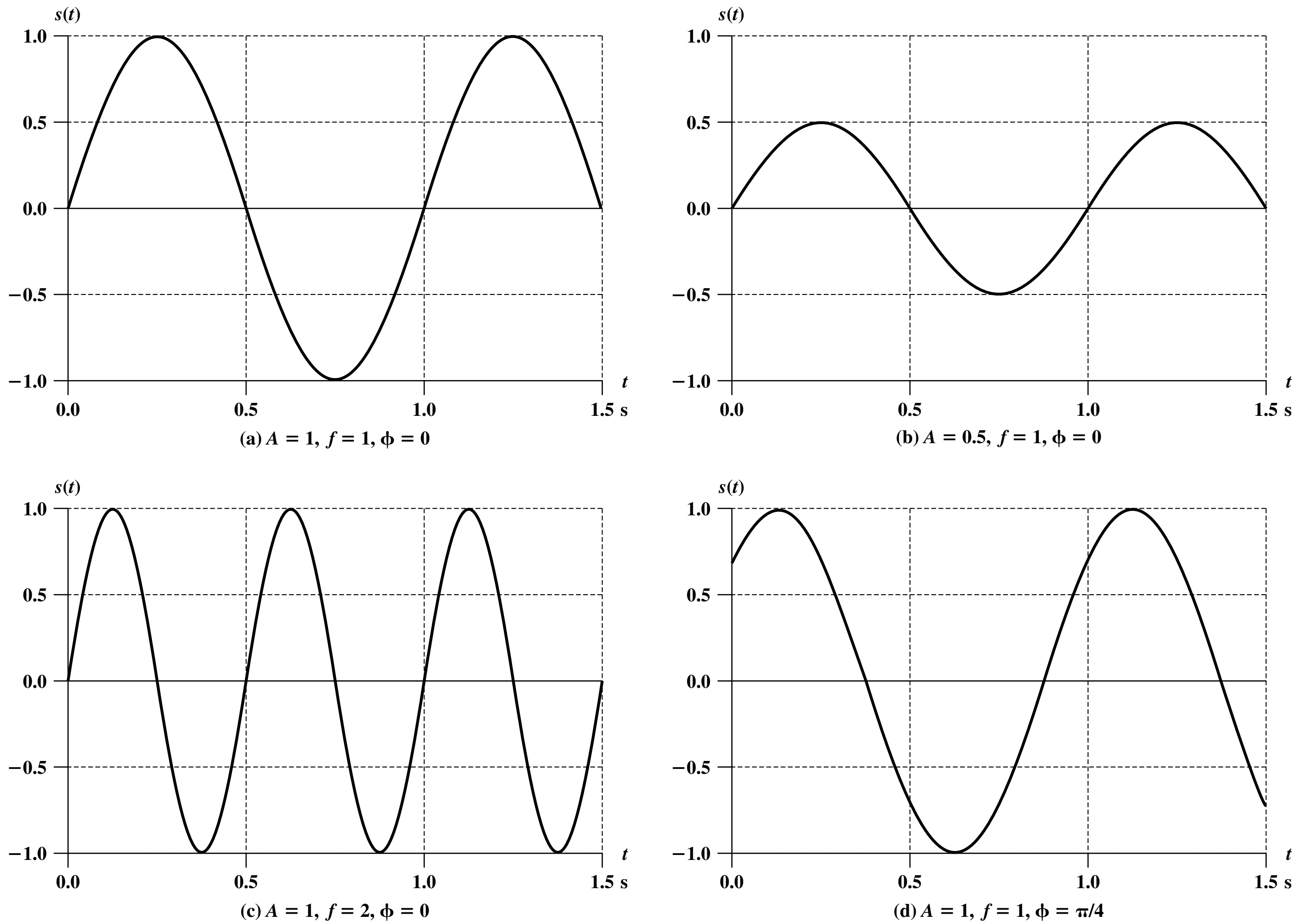

Figure 3 $s(t) = A \sin(2\pi f t + \phi)$

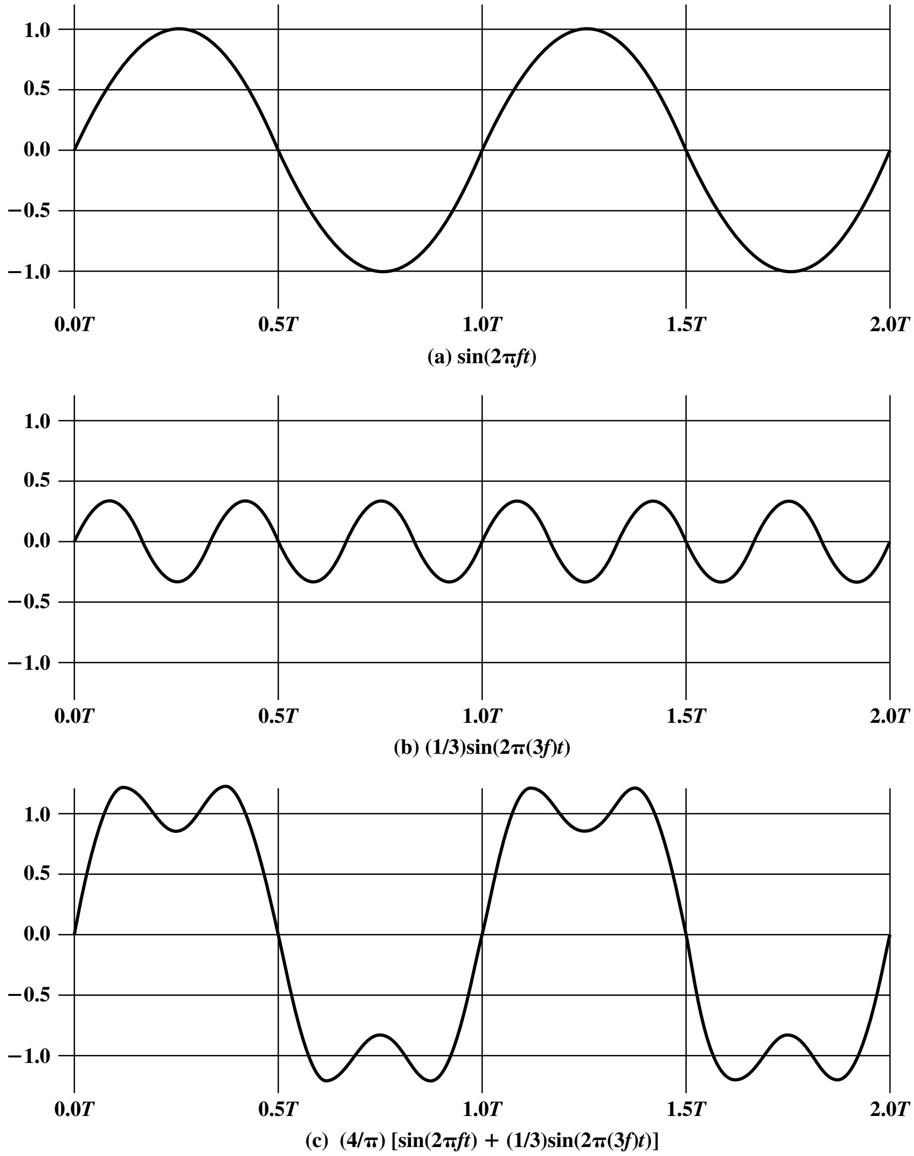

Figure 4 Addition of Frequency Components ($T = 1/f$)

amplitude, frequency, and phase, any electromagnetic signal can be constructed. Put another way, any electromagnetic signal can be shown to consist of a collection of periodic analog signals (sine waves) at different amplitudes, frequencies, and phases. The importance of being able to look at a signal from the frequency perspective (frequency domain) rather than a time perspective (time domain) should become clear as the discussion proceeds.

The **spectrum** of a signal is the range of frequencies that it contains. For the signal of Figure 4c, the spectrum extends from f to $3f$. The **absolute bandwidth** of a signal is the width of the spectrum. In the case of Figure 4c, the bandwidth is $3f - f = 2f$. Many signals have an infinite bandwidth, but with most of the energy contained in a relatively narrow band of frequencies. This band is referred to as the **effective bandwidth**, or just **bandwidth**.

Relationship between Data Rate and Bandwidth

There is a direct relationship between the information-carrying capacity of a signal and its bandwidth: The greater the bandwidth, the higher the information-carrying capacity. As a very simple example, consider the square wave of Figure 2b. Suppose that we let a positive pulse represent binary 0 and a negative pulse represent binary 1. Then the waveform represents the binary stream 0101. . . . The duration of each pulse is $1/(2f)$; thus the data rate is $2f$ bits per second (bps). What are the frequency components of this signal? To answer this question, consider again Figure 4. By adding together sine waves at frequencies f and $3f$, we get a waveform that begins to resemble the square wave. Let us continue this process by adding a sine wave of frequency $5f$, as shown in Figure 5a, and then adding a sine wave of frequency $7f$, as shown in Figure 5b. As we add additional odd multiples of f, suitably scaled, the resulting waveform approaches that of a square wave more and more closely.

Indeed, it can be shown that the frequency components of the square wave with amplitudes A and $-A$ can be expressed as follows:

$$s(t) = A \times \frac{4}{\pi} \sum_{k \text{ odd}, k=1}^{\infty} \frac{\sin(2\pi kft)}{k}$$

This waveform has an infinite number of frequency components and hence an infinite bandwidth. However, the peak amplitude of the kth frequency component, kf, is only $1/k$, so most of the energy in this waveform is in the first few frequency components. What happens if we limit the bandwidth to just the first three frequency components? We have already seen the answer, in Figure 5a. As we can see, the shape of the resulting waveform is reasonably close to that of the original square wave.

We can use Figures 4 and 5 to illustrate the relationship between data rate and bandwidth. Suppose that we are using a digital transmission system that is capable of transmitting signals with a bandwidth of 4 MHz. Let us attempt to transmit a sequence of alternating 0s and 1s as the square wave of Figure 5c. What data rate can be achieved? We look at three cases.

Case I. Let us approximate our square wave with the waveform of Figure 5a. Although this waveform is a "distorted" square wave, it is sufficiently close to the square wave that a receiver should be able to discriminate between a binary 0 and a binary 1. If we let $f = 10^6$ cycles/second = 1 MHz, then the bandwidth of the signal

$$s(t) = \frac{4}{\pi} \times \left[\sin((2\pi \times 10^6)t) + \frac{1}{3}\sin((2\pi \times 3 \times 10^6)t) + \frac{1}{5}\sin((2\pi \times 5 \times 10^6)t)\right]$$

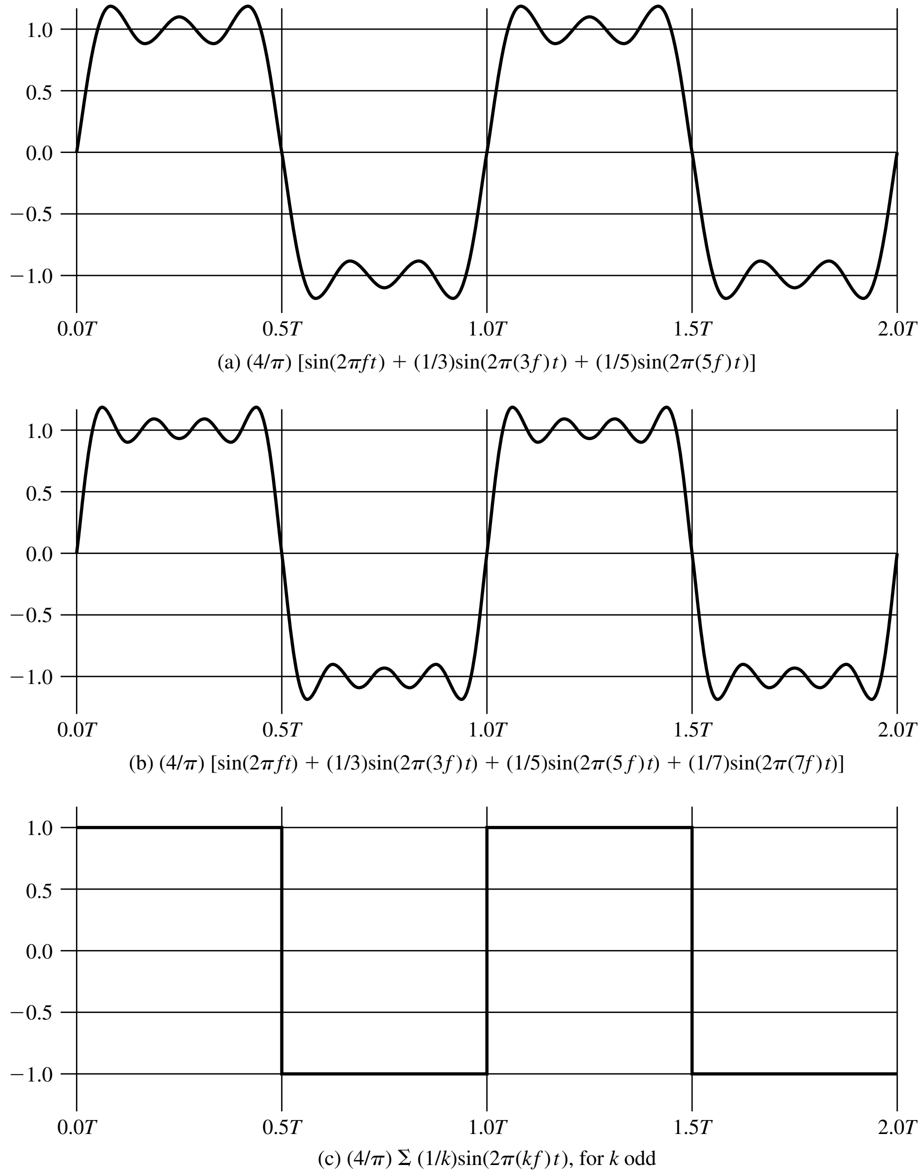

Figure 5 Frequency Components of Square Wave ($T = 1/f$)

is $(5 \times 10^6) - 10^6 = 4$ MHz. Note that for $f = 1$ MHz, the period of the fundamental frequency is $T = 1/10^6 = 10^{-6} = 1\ \mu s$. If we treat this waveform as a bit string of 1s and 0s, one bit occurs every $0.5\ \mu s$, for a data rate of $2 \times 10^6 = 2$ Mbps. Thus, for a bandwidth of 4 MHz, a data rate of 2 Mbps is achieved.

Case II. Now suppose that we have a bandwidth of 8 MHz. Let us look again at Figure 5a, but now with $f = 2$ MHz. Using the same line of reasoning as before, the bandwidth of the signal is $(5 \times 2 \times 10^6) - (2 \times 10^6) = 8$ MHz. But in this case $T = 1/f = 0.5\ \mu$s. As a result, one bit occurs every 0.25 μs for a data rate of 4 Mbps. Thus, other things being equal, by doubling the bandwidth, we double the potential data rate.

Case III. Now suppose that the waveform of Figure 4c is considered adequate for approximating a square wave. That is, the difference between a positive and negative pulse in Figure 4c is sufficiently distinct that the waveform can be used successfully to represent a sequence of 1s and 0s. Assume as in Case II that $f = 2$ MHz and $T = 1/f = 0.5\ \mu$s, so that one bit occurs every 0.25 μs for a data rate of 4 Mbps. Using the waveform of Figure 4c, the bandwidth of the signal is $(3 \times 2 \times 10^6) - (2 \times 10^6) = 4$ MHz. Thus, a given bandwidth can support various data rates depending on the ability of the receiver to discern the difference between 0 and 1 in the presence of noise and other impairments.

To summarize,

- **Case I:** Bandwidth = 4 MHz; data rate = 2 Mbps
- **Case II:** Bandwidth = 8 MHz; data rate = 4 Mbps
- **Case III:** Bandwidth = 4 MHz; data rate = 4 Mbps

We can draw the following conclusions from the preceding discussion. In general, any digital waveform will have infinite bandwidth. If we attempt to transmit this waveform as a signal over any medium, the transmission system will limit the bandwidth that can be transmitted. Furthermore, for any given medium, the greater the bandwidth transmitted, the greater the cost. Thus, on the one hand, economic and practical reasons dictate that digital information be approximated by a signal of limited bandwidth. On the other hand, limiting the bandwidth creates distortions, which makes the task of interpreting the received signal more difficult. The more limited the bandwidth, the greater the distortion and the greater the potential for error by the receiver.

2 ANALOG AND DIGITAL DATA TRANSMISSION

The terms *analog* and *digital* correspond, roughly, to *continuous* and *discrete*, respectively. These two terms are used frequently in data communications in at least three contexts: data, signals, and transmission.

Briefly, we define **data** as entities that convey meaning, or information. **Signals** are electric or electromagnetic representations of data. **Transmission** is the communication of data by the propagation and processing of signals. In what follows, we try to make these abstract concepts clear by discussing the terms *analog* and *digital* as applied to data, signals, and transmission.

Analog and Digital Data

The concepts of analog and digital data are simple enough. Analog data take on continuous values in some interval. For example, voice and video are continuously