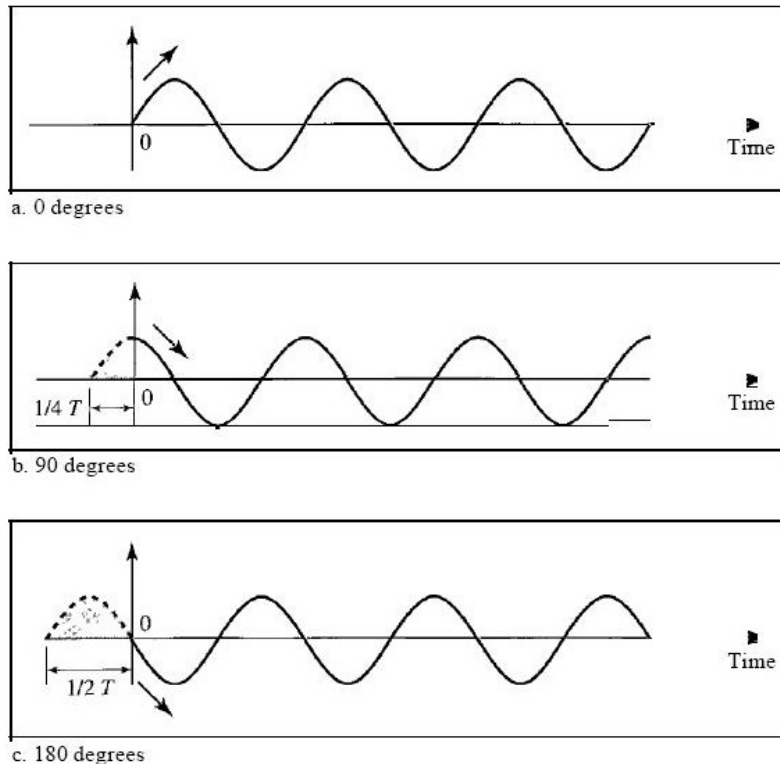


Notes on Phase

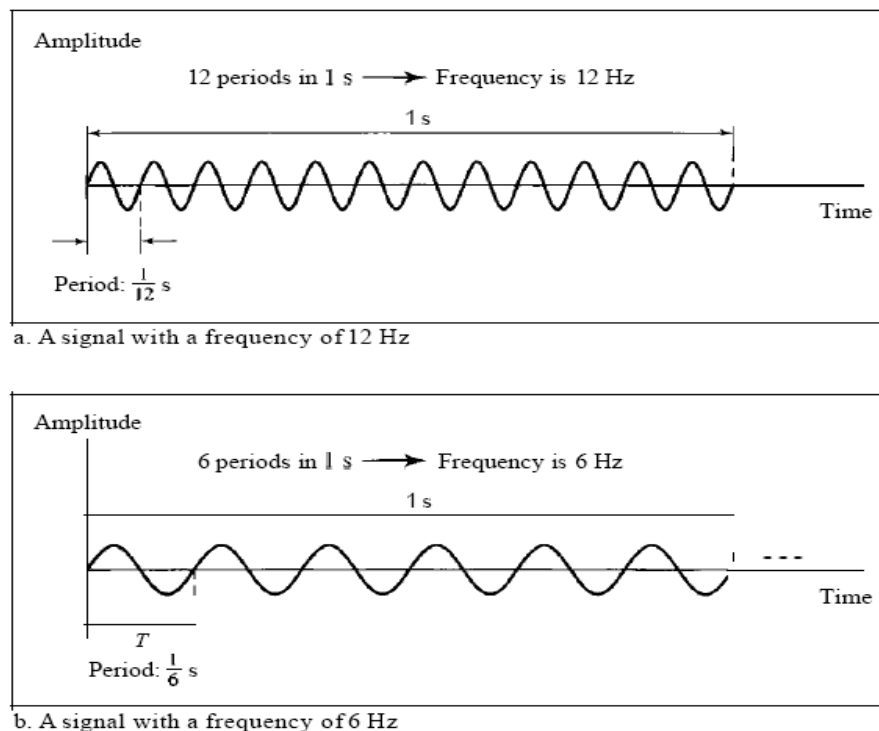
Figure 3.5 Three sine waves with the same amplitude and frequency, but different phases



Looking at Figure 3.5, we can say that

1. A sine wave with a phase of 0° starts at time 0 with a zero amplitude. The amplitude is increasing.
2. A sine wave with a phase of 90° starts at time 0 with a peak amplitude. The amplitude is decreasing.
3. A sine wave with a phase of 180° starts at time 0 with a zero amplitude. The amplitude is decreasing.

Figure 3.4 Two signals with the same amplitude and phase, but different frequencies



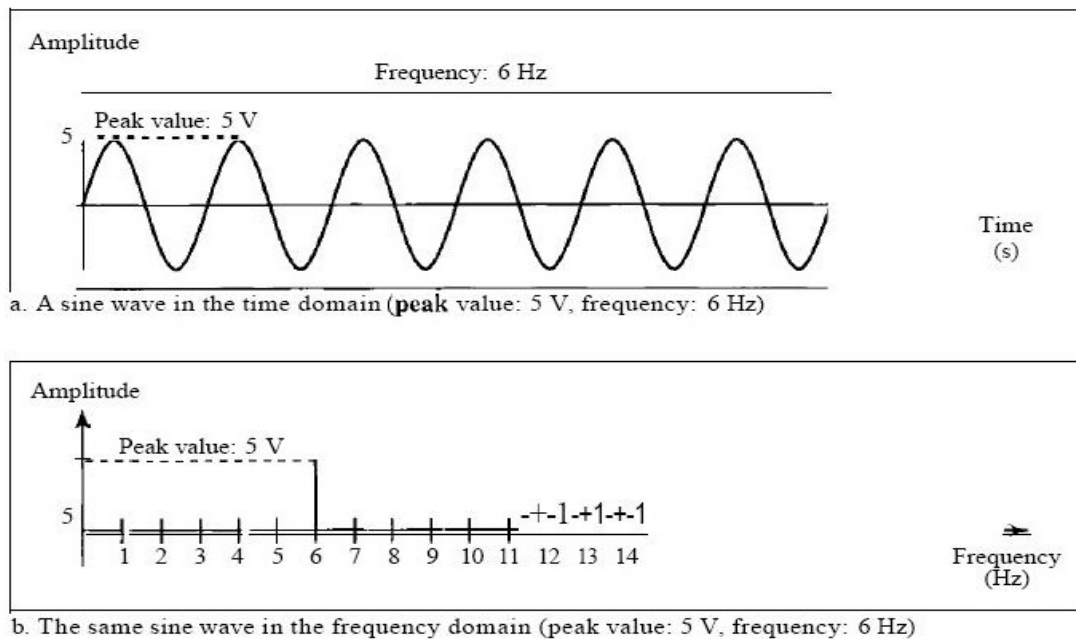
Time and Frequency Domains

A sine wave is comprehensively defined by its amplitude, frequency, and phase. We have been showing a sine wave by using what is called a time-domain plot. The time-domain plot shows changes in signal amplitude with respect to time (it is an amplitude-versus-time plot). Phase is not explicitly shown on a time-domain plot.

To show the relationship between amplitude and frequency, we can use what is called a frequency-domain plot. A frequency-domain plot is concerned with only the peak value and the frequency. Changes of amplitude during one period are not shown.

Figure below shows a signal in both the time and frequency domains.

Figure 3.7 The time-domain and frequency-domain plots of a sine wave



Composite Signals

So far, we have focused on simple sine waves. Simple sine waves have many applications in daily life. We can send a single sine wave to carry electric energy from one place to another. For example, the power company sends a single sine wave with a frequency of 60 Hz to distribute electric energy to houses and businesses.

If we had only one single sine wave to convey a conversation over the phone, it would make no sense and carry no information. We would just hear a buzz.

A composite signal is made of many simple sine waves.

A single frequency sine wave is not useful in data communications; we need to send a composite signal, a signal made of many simple sine waves.

In the early 1900s, the French mathematician Jean-Baptiste Fourier showed that any composite signal is actually a combination of simple sine waves with different frequencies. According to Fourier analysis, any composite signal is a combination of simple sine waves with different frequencies, amplitudes, and phases.

A composite signal can be periodic or nonperiodic. A periodic composite signal can be decomposed into a series of simple sine waves with discrete frequencies that have integer values (1, 2, 3, and so on). A nonperiodic composite signal can be decomposed into a combination of an infinite number of simple sine waves with continuous frequencies, frequencies that have real values.

If the composite signal is periodic, the decomposition gives a series of signals with discrete frequencies; if the composite signal is nonperiodic, the decomposition gives a combination of sine waves with continuous frequencies.

Example 3.8

Figure 3.9 shows a periodic composite signal with frequency f , *this* type of signal is not typical of those found in data communications. The analysis of this signal can give us a good understanding of how to decompose signals.

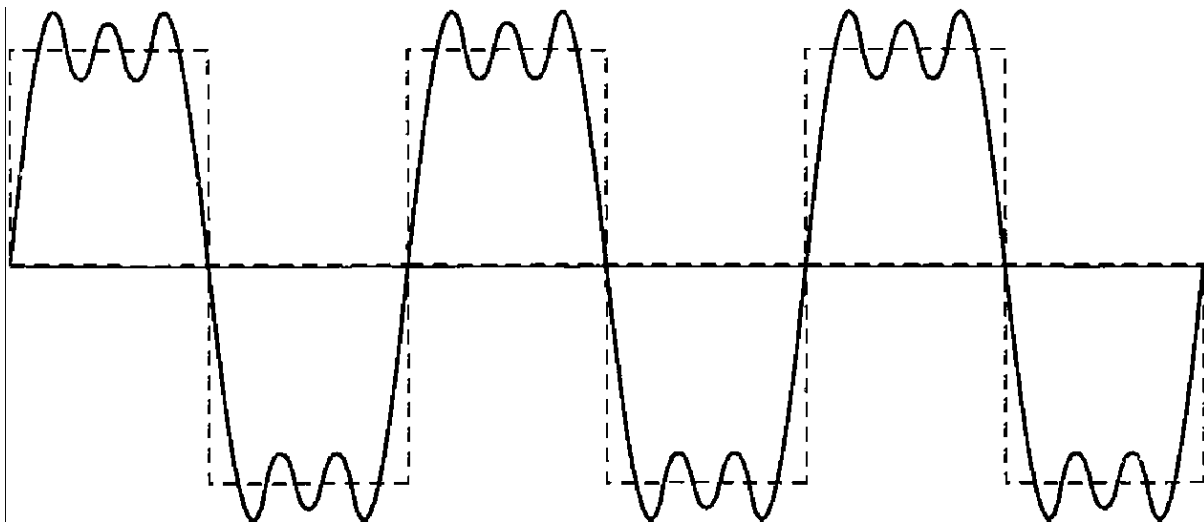
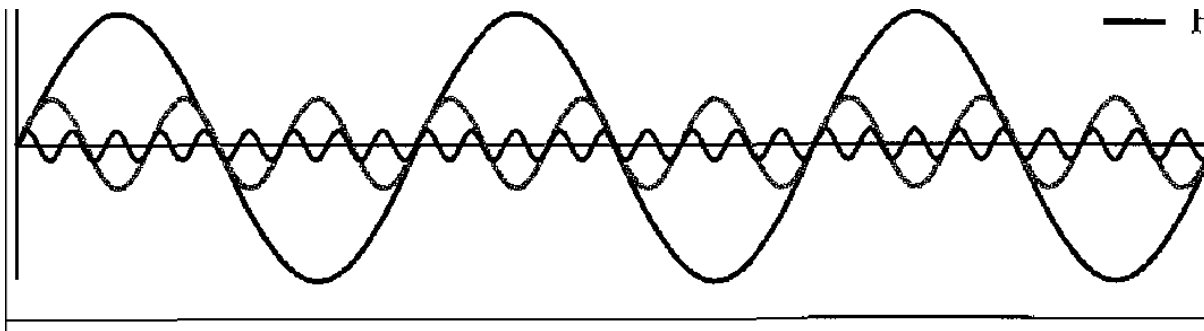
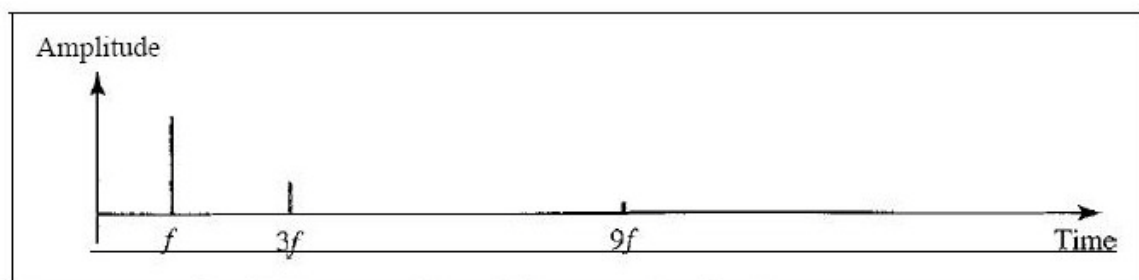


Figure 3.10 shows the result of decomposing the above signal in both the time and frequency domains.



Time domain



b. Frequency-domain decomposition of the composite signal

figure (3.10)

The amplitude of the sine wave with frequency f is almost the same as the peak amplitude of the composite signal. The amplitude of the sine wave with frequency $3f$ is one-third of that of the first, and the amplitude of the sine wave with frequency $9f$ is one-ninth of the first. The frequency of the sine wave with frequency f is the same as the frequency of the composite signal; it is called the fundamental frequency, or first harmonic. The sine wave with frequency $3f$ has a frequency of 3 times the fundamental frequency; it is called the third harmonic. The third sine wave with frequency $9f$ has a frequency of 9 times the fundamental frequency; it is called the ninth harmonic.

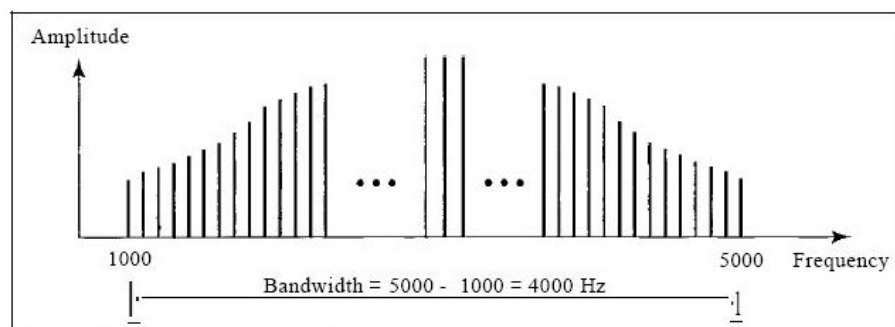
Bandwidth

The range of frequencies contained in a composite signal is its bandwidth. The bandwidth is normally a difference between two numbers. For example, if a composite signal contains frequencies between 1000 and 5000, its bandwidth is $5000 - 1000$, or 4000.

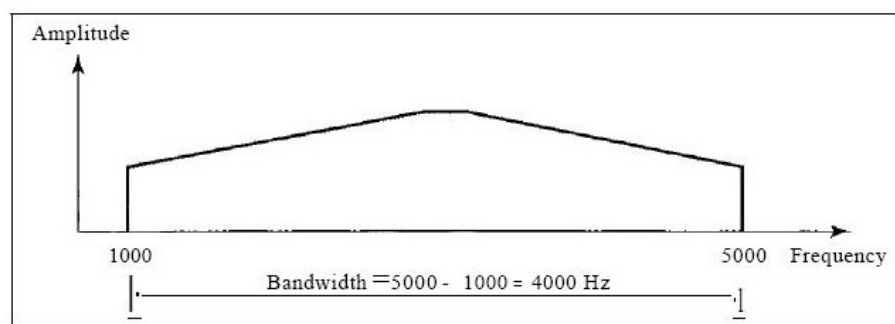
The bandwidth of a composite signal is the difference between the highest and the lowest frequencies contained in that signal.

Figure 3.12 shows the concept of bandwidth.

Figure 3.12 The bandwidth of periodic and nonperiodic composite signals



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

The figure depicts two composite signals, one periodic and the other nonperiodic. The bandwidth of the periodic signal contains all integer frequencies between 1000 and 5000 (1000, 1001, 1002, ...). The bandwidth of the nonperiodic signals has the same range, but the frequencies are continuous.

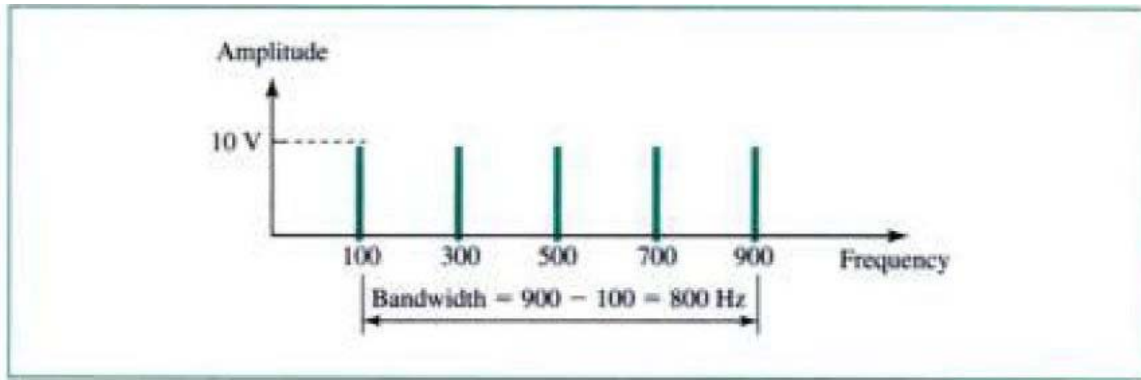
Example 3.10

If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth? Draw the spectrum, assuming all components have a maximum amplitude of 10 V.

Solution:

Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. Then $B = f_h - f_l = 900 - 100 = 800$ Hz

The spectrum has only five spikes, at 100, 300, 500, 700, and 900 Hz (see Figure 3.13).

**Example 3.11**

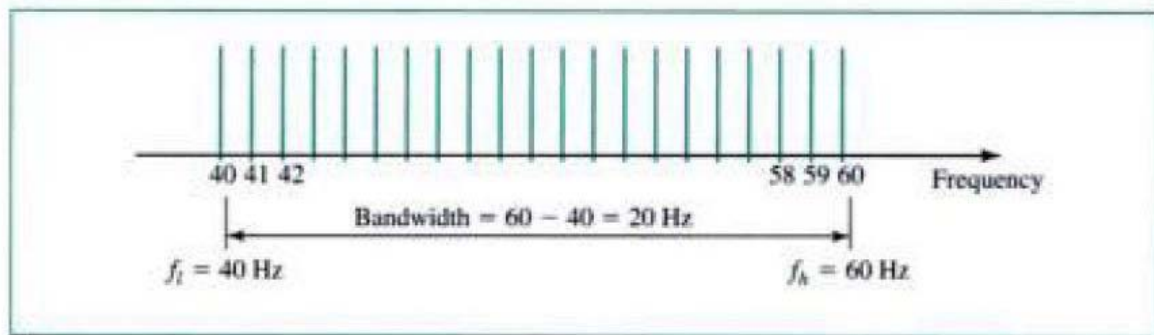
A periodic signal has a bandwidth of 20 Hz. The highest frequency is 60 Hz. What is the lowest frequency? Draw the spectrum if the signal contains all frequencies of the same amplitude.

Solution:

Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. Then

$$B = f_h - f_l \rightarrow 20 = 60 - f_l \rightarrow f_l = 60 - 20 = 40 \text{ Hz}$$

The spectrum contains all integer frequencies. We show this by a series of spikes (see Figure 3.14).

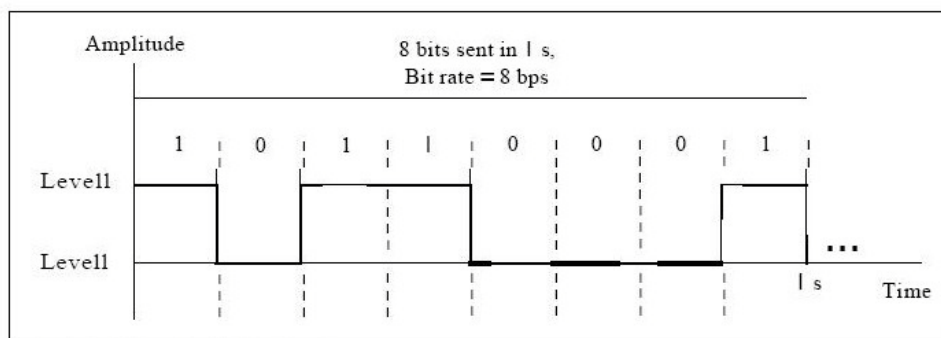


3.3 DIGITAL SIGNALS

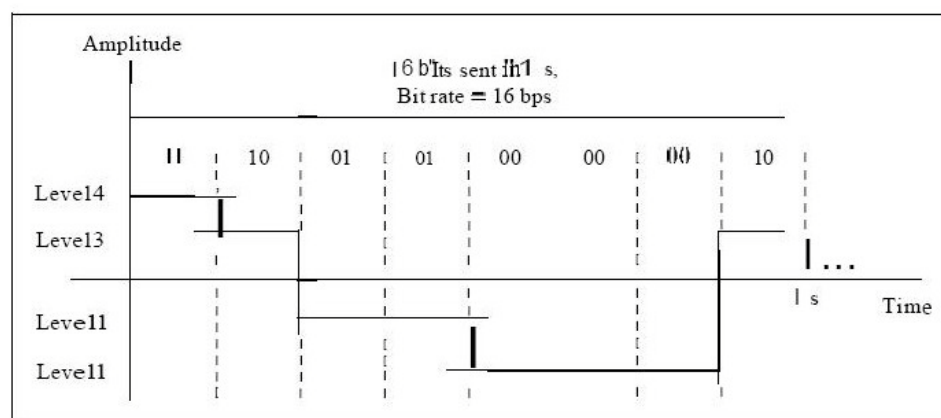
In addition to being represented by an analog signal, information can also be represented by a digital signal. For example, a 1 can be encoded as a positive voltage and a 0 as zero voltage. A digital signal can have more than two levels. In this case, we can send more than 1 bit for each level. Figure 3.16 shows two signals, one with two levels and the other with four.

Figure 3.16 Two digital signals: one with two signal levels and the other with four signal levels

Figure 3.16 Two digital signals: one with two signal levels and the other with four signal levels



a. A digital signal with two levels



b. A digital signal with four levels

We send 1 bit per level in part a of the figure and 2 bits per level in part b of the figure. In general, if a signal has L levels, each level needs $\log L$ bits.

Example 3.16

A digital signal has eight levels. How many bits are needed per level? We calculate the number of bits from the formula

Number of bits per level = $\log 8 = 3$

Each signal level is represented by 3 bits.

Bit Rate

Most digital signals are nonperiodic, and thus period and frequency are not appropriate characteristics. Another *term-bit rate* (instead of *frequency*)-is used to describe digital signals. The bit rate is the number of bits sent in 1s, expressed in bits per second (bps). Figure 3.16 shows the bit rate for two signals.

Example 3.18

Assume we need to download text documents that have of 100 pages . What is the required bit rate of the channel?

Solution:

A page is an average of 24 lines with 80 characters in each line. If we assume that one character requires 8 bits, the bit rate is

$100 \times 24 \times 80 \times 8 = 1,636,000 \text{ bps} = 1.636 \text{ Mbps}$

Bit Length

The bit length is the distance one bit occupies on the transmission medium.

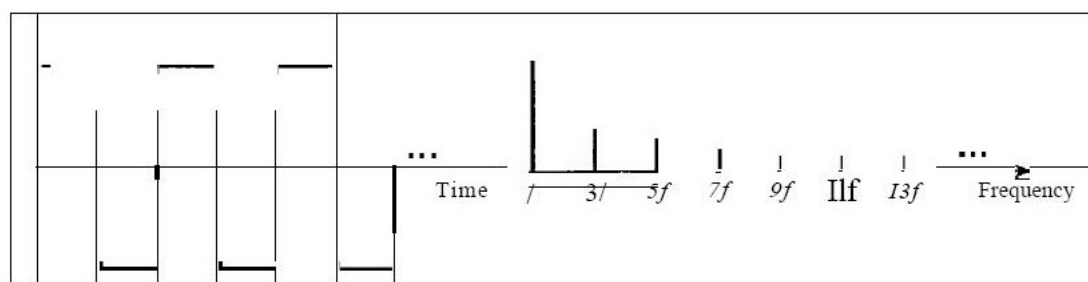
Bit length = propagation speed x bit duration

Digital Signal as a Composite Analog Signal

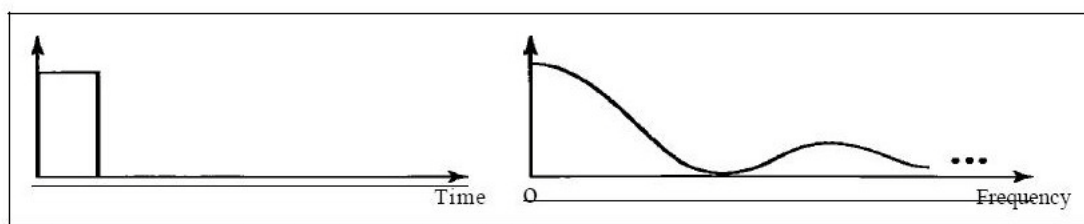
Based on Fourier analysis, a digital signal is a composite analog signal. The bandwidth is infinite, as you may have guessed. We can intuitively come up with this concept when we consider a digital signal. A digital signal, in the time domain, comprises connected vertical and horizontal line segments. A vertical line in the time domain means a frequency of infinity (sudden change in time); a horizontal line in the time domain means a frequency of zero (no change in time). Going from a frequency of zero to a frequency of infinity (and vice versa) implies all frequencies in between are part of the domain.

Fourier analysis can be used to decompose a digital signal. If the digital signal is periodic, which is rare in data communications, the decomposed signal has a frequency domain representation with an infinite bandwidth and discrete frequencies. If the digital signal is nonperiodic, the decomposed signal still has an infinite bandwidth, but the frequencies are continuous. Figure 3.17 shows a periodic and a nonperiodic digital signal and their bandwidths.

Figure 3.17 The time and frequency domains of periodic and nonperiodic digital signals



a. Time and frequency domains of periodic digital signal



b. Time and frequency domains of nonperiodic digital signal

Transmission of Digital Signals

The previous discussion asserts that a digital signal, periodic or nonperiodic, is a composite analog signal with frequencies between zero and infinity. For the remainder of the discussion, let us consider the case of a nonperiodic digital signal, similar to the ones we encounter in data communications. The fundamental question is, How can we send a digital signal from point *A* to point *B*? We can transmit a digital signal by using one of two different approaches: baseband transmission or broadband transmission (using modulation).

1- Baseband Transmission

Baseband transmission means sending a digital signal over a channel without changing the digital signal to an analog signal.

2- Broadband Transmission (Using Modulation)

Broadband transmission or modulation means changing the digital signal to an analog signal for transmission.

Medium Bandwidth and Significant Bandwidth:

A transmission medium has a limited bandwidth which mean that it can transfer only a some range of frequencies. A transmission medium with a particular bandwidth is capable of transmitting only digital signals whose significant bandwidth is less than the bandwidth of the medium. If a signal is sent on a transmission medium whose bandwidth is less than the required significant bandwidth, the signal may be so distorted that it is not recognizable at the receiver.

Medium Bandwidth and Data Rate (Channel Capacity)

The significant bandwidth of a signal increases with bit rate. This means when the bit rate is increased, we have wider significant bandwidth, and consequently we need medium with wider bandwidth to transfer that signal. The maximum bit rate a transmission medium can transfer is called channel capacity of the medium. for example , a normal telephone line with a bandwidth of 3000 Hz is capable of transferring up to 20000 bps, but other factors can decrease this rate.