Short notes on Computer Networks and Data Communication

Topics:
Physical Layer Details and Specifications
Physical Layer capacity and optimization, hardware basic

DATA AND SIGNALS

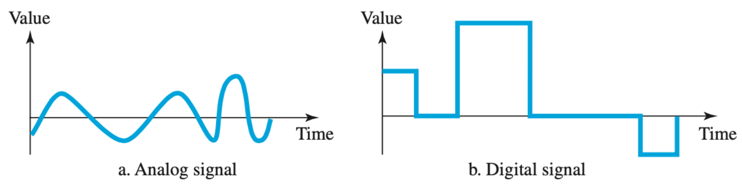
ANALOGUE AND DIGITAL DATA

Data can be analog or digital. The term analog data refers to continuous information; digital data refers to information that has discrete states. For example, an analog clock with hour, minute, and second hands gives information in a continuous form; the movements of the hands are continuous. On the other hand, a digital clock that reports the hours and the minutes will change suddenly from 8:05 to 8:06.

ANALOG AND DIGITAL SIGNALS

Like the data they represent, signals can be either analog or digital. An analog signal has infinitely many levels of intensity over a period of time. As the wave moves from value A to value B, it passes through and includes an infinite number of values along its path. A digital signal, on the other hand, can have only a limited number of defined values. Although each value can be any number, it is often as simple as 1 and 0.

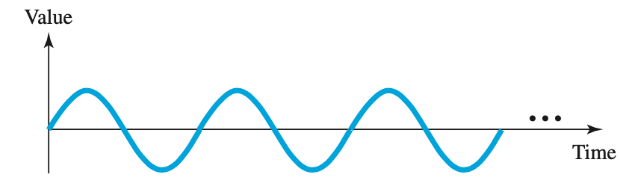
Comparison of analog and digital signals



PERIODIC AND NONPERIODIC

A periodic signal completes a pattern within a measurable time frame, called a period, and repeats that pattern over subsequent identical periods. The completion of one full pattern is called a cycle. A nonperiodic signal changes without exhibiting a pattern or cycle that repeats over time.
The sine wave is the most fundamental form of a periodic analog signal.

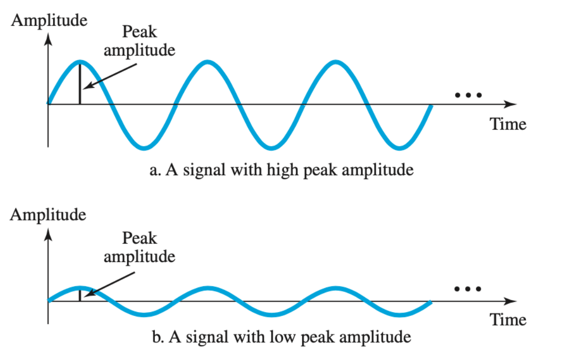
A sine wave



SIGNAL ATTRIBUTES

1. Peak Amplitude
   The peak amplitude of a signal is the absolute value of its highest intensity, proportional to the energy it carries. For electric signals, peak amplitude is normally measured in volts.

Two signals with the same phase and frequency, but different amplitudes



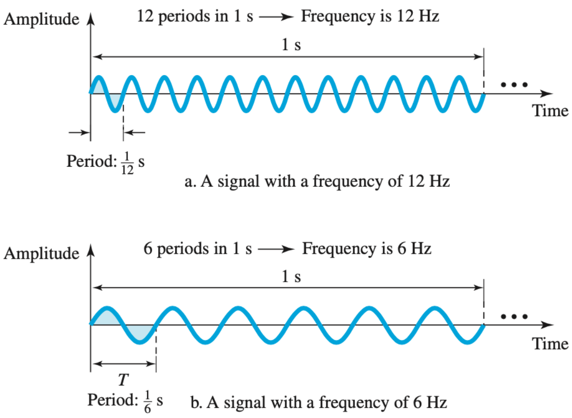
2. Period and Frequency
   Period refers to the amount of time, in seconds, a signal needs to complete one cycle. Frequency refers to the number of periods in 1 s. Note that period and frequency are just two characteristics defined in two

ways. As the following formulas show, the period is the inverse of frequency, and frequency is the inverse of the period.

$$f = 1/T$$

A period is formally expressed in seconds. Frequency is formally expressed in Hertz (Hz), a cycle per second.

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



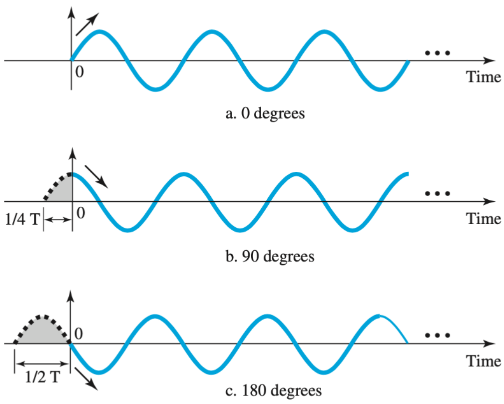
a. A signal with a frequency of 12 Hz

b. A signal with a frequency of 6 Hz

3. Phase

The term phase, or phase shift, describes the position of the waveform relative to time 0. If we think of the wave as something that can be shifted backward or forward along the time axis, phase describes the amount of that shift. It indicates the status of the first cycle. Phase is measured in degrees or radians [360^o is 2π rad; 1^o is $2\pi/360$ rad, and 1 rad is $360/(2\pi)$].

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



a. 0 degrees

b. 90 degrees

c. 180 degrees

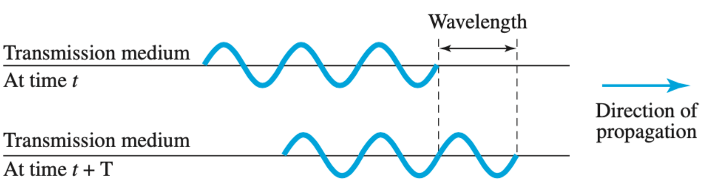
4. Wavelength

Wavelength is another characteristic of a signal traveling through a transmission medium. Wavelength binds the period or the frequency of a simple sine wave to the propagation speed of the medium.

Wavelength = (propagation speed) x period

Or, $\lambda = c/f$

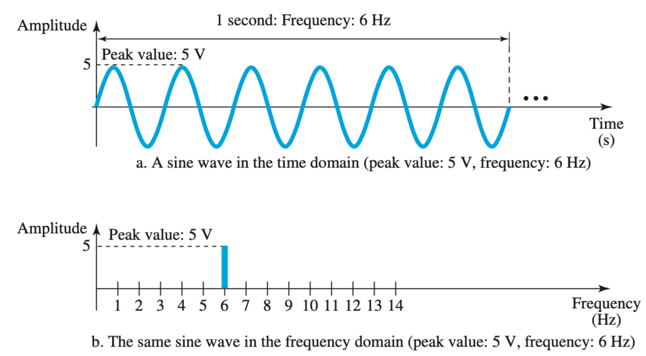
Wavelength and period



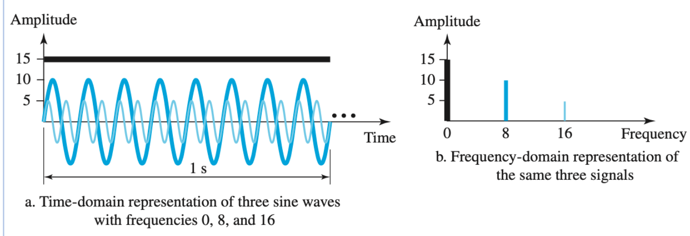
5. Time and Frequency Domains

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 concerning time (it is an amplitude-versus-time 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.

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

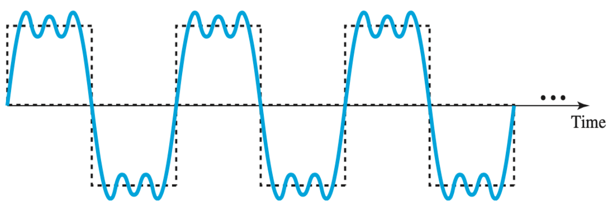


The time domain and frequency domain of three sine waves



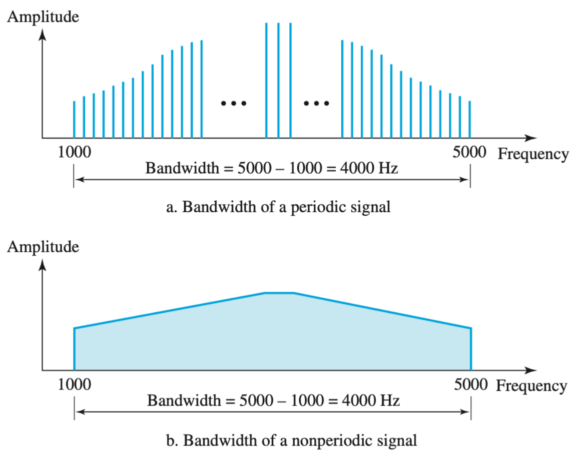
6. Composite signals
   A single-frequency sine wave is not useful in data communications; we need to send a composite signal, a signal made of many simple sine waves. any composite signal combines simple sine waves with different frequencies, amplitudes, and phases.

A composite periodic signal



7. 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.

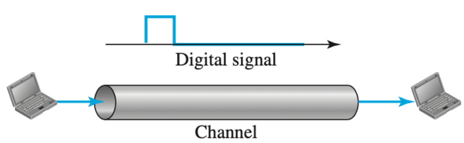
The bandwidth of periodic and nonperiodic composite signals



TRANSMISSION OF DIGITAL SIGNALS

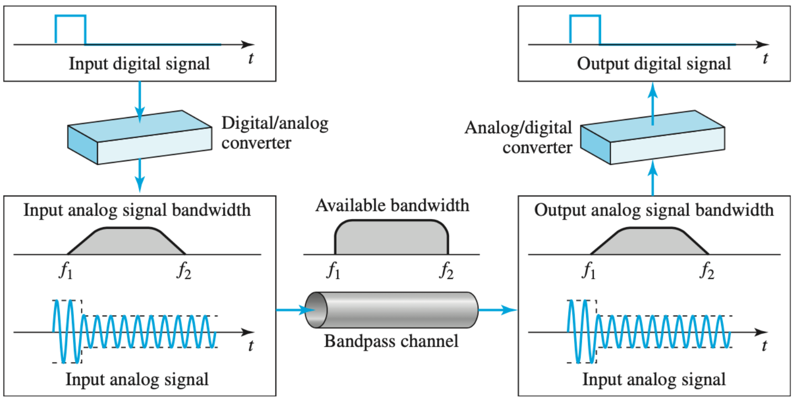
1. Baseband Transmission
   Baseband transmission means sending a digital signal over a channel without changing the digital signal to an analog signal. Baseband transmission requires that we have a **low-pass channel,** a channel with a bandwidth that starts from frequency zero.

Baseband transmission



2. Broadband Transmission (Using Modulation)
Broadband transmission or modulation means changing the digital signal to an analog signal for transmission. Modulation allows us to use a bandpass channel—a channel with a bandwidth that does not start from zero. This type of channel is more available than a low-pass channel.

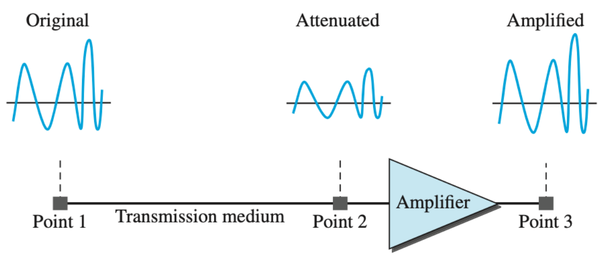
Modulation of a digital signal for transmission on a bandpass channel



TRANSMISSION ISSUES

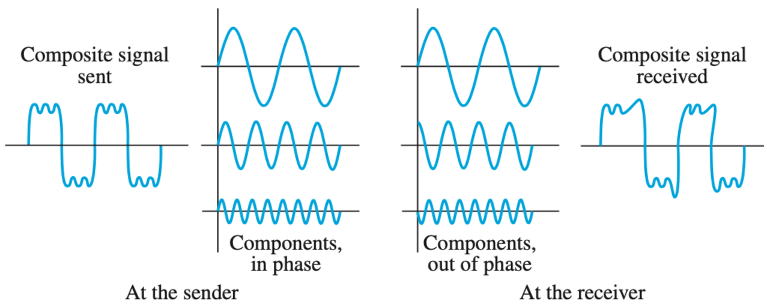
1) Attenuation
Attenuation means a loss of energy. When a signal, simple or composite, travels through a medium, it loses some of its energy in overcoming the medium's resistance. That is why a wire carrying electric signals gets warm, if not hot, after a while. Some of the electrical energy in the signal is converted to heat. To compensate for this loss, amplifiers are used to amplify the signal.

Attenuation



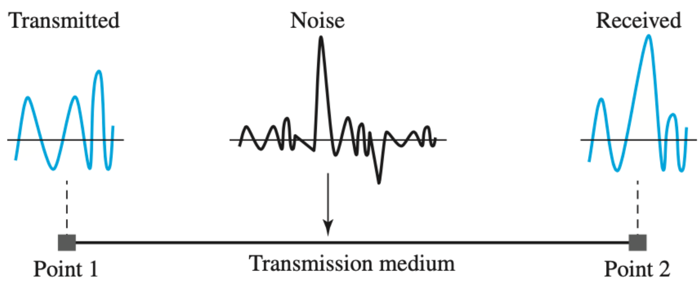
2) Distortion
Distortion means that the signal changes its form or shape.

Distortion



3) Noise
Noise is another cause of signal corruption. Several types of noise, such as thermal noise, induced noise, crosstalk, and impulse noise, may corrupt the signal. Thermal noise is the random motion of electrons in a wire, which creates an extra signal not originally sent by the transmitter. Induced noise comes from sources such as motors and appliances. Crosstalk is the effect of one wire on the other. Impulse noise is a spike (a signal with high energy in a very short time) that comes from power lines, lightning, etc.

Noise



DATA RATE LIMITS

A very important consideration in data communications is how fast we can send data, in bits per second, over a channel. The data rate depends on three factors:

1. The bandwidth available
2. The level of the signals we use
3. The quality of the channel (the level of noise)

1. Noiseless Channel: Nyquist Bit Rate

   The Nyquist bit rate formula defines the theoretical maximum bit rate for a noiseless channel.

   $$\text{Max BitRate} = 2B \times \log_2 L$$

   In this formula, B is the channel's bandwidth, L is the number of signal levels used to represent data, and BitRate is the bit rate in bits per second.
2. Noisy Channel: Shannon Capacity

   In reality, we cannot have a noiseless channel; the channel is always noisy. Claude Shannon introduced a formula called the Shannon capacity to determine the theoretical highest data rate for a noisy channel:

   $$\text{Max BitRate} = B \log_2 (1 + S/N)$$

   The amount of thermal noise present is measured by the ratio of the signal power to the noise power, called the **SNR (Signal-to-Noise Ratio).** If we denote the signal power by S and the noise power by N, the signal-to-noise ratio is S/N. Usually, the ratio is expressed on a *log scale* as the quantity $10 \log_{10} (S / N)$ because it can vary over a tremendous range. The units of this log scale are called decibels (dB).
3. Throughput

   The throughput measures how fast we can send data through a network (bits/sec). Although, at first glance, bandwidth in bits per second and throughput seem the same, they are different. A link may have a bandwidth of B bps, but we can only send T bps through this link, with T always less than B. In other words, the bandwidth is a potential measurement of a link; the throughput is an actual measurement of how fast we can send data.
4. Latency (Delay)

   The latency or delay defines how long it takes for an entire message to completely arrive at the destination from when the first bit is sent out from the source. Latency comprises four components: propagation time, transmission time, queuing time, and processing delay. Propagation time (Distance / (Propagation Speed)) measures the time required for a bit to travel from the source to the destination. The transmission time ((Message size) / Bandwidth) of a message depends on the size of the message and the bandwidth of the channel. Queuing time is the time needed for each intermediate or end device to hold the message before it can be processed.
5. Jitter

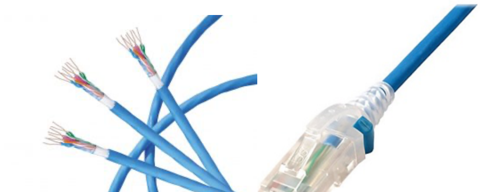
   Another performance issue that is related to delay is jitter. We can roughly say that jitter is a problem if different packets of data encounter different delays and the application using the data at the receiver site is time-sensitive (audio and video data, for example).

GUIDED TRANSMISSION MEDIA

1. Twisted Pairs

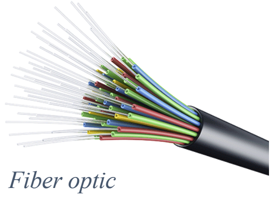
   A twisted pair comprises two insulated copper wires, typically about 1 mm thick. The wires are twisted together helically, just like a DNA molecule. Twisting is done because two parallel wires constitute a fine antenna, causing noise. When the wires are twisted, the waves from different twists cancel out, so the wire radiates less effectively.

2. Coaxial Cable
   Another common transmission medium is the coaxial cable (known to its many friends as ‘‘coax’’ and pronounced ‘‘co-ax’’). It has better shielding and greater bandwidth than unshielded twisted pairs to span longer distances at higher speeds.
3. Fiber optics
   Fiber optics are used for long-haul transmission in network backbones, high-speed LANs (although so far, copper has always managed to catch up eventually), and high-speed Internet. An optical transmission system has three key components: the light source, the transmission medium, and the detector. Conventionally, a pulse of light indicates a 1 bit, and the absence of light indicates a 0 bit.



Twisted pair

Coaxial



Fiber optic

UNGUIDED TRANSMISSION
1. Radio Transmission
   Radiofrequency (RF) waves are easy to generate, can travel long distances, and can penetrate buildings easily, so they are widely used for indoor and outdoor communication. Radio waves are also omnidirectional, meaning they travel in all directions from the source, so the transmitter and receiver do not have to be physically carefully aligned.
2. Microwave Transmission
   Above 100 MHz, the waves travel in nearly straight lines and can therefore be narrowly focused. Microwaves travel in a straight line, so the earth will get in the way if the towers are too far apart. Thus, repeaters are needed periodically. The higher the towers are, the farther apart they can be.
3. Infrared Transmission
   Unguided infrared waves are widely used for short-range communication. The remote controls used for televisions, VCRs, and stereos all use infrared communication. They are relatively directional, cheap, and easy to build but have a major drawback: they do not pass through solid objects.
4. Light Transmission
   Unguided optical signaling or free-space optics has been in use for centuries. A more modern application is to connect the LANs in two buildings via lasers mounted on their rooftops. Optical signaling using lasers is inherently unidirectional, so each end needs its own laser and its own photodetectors.

DIGITAL MODULATION AND MULTIPLEXING
To send digital information, we must devise signals to represent bits. The process of converting between bits and signals that represent them is called digital modulation.

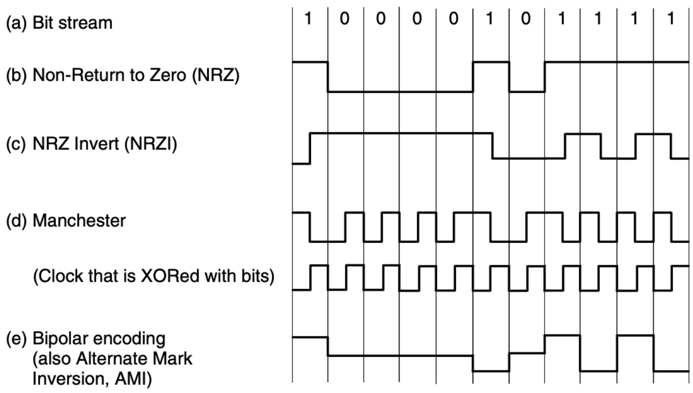


Figure 2-20. Line codes: (a) Bits, (b) NRZ, (c) NRZI, (d) Manchester, (e) Bipolar or AMI.

This signal will not look exactly like the signal that was sent. The channel and noise at the receiver will attenuate and distort it. The receiver maps the signal samples to decode the bits to the closest symbols. For NRZ, a positive voltage will be taken to indicate that a 1 was sent, and a negative voltage will be taken to indicate that a 0 was sent.

Digital modulation is often accomplished by regulating or modulating a carrier signal that sits in the passband. We can modulate the carrier signal's amplitude, frequency, or phase. Each of these methods has a corresponding name. In ASK (Amplitude Shift Keying), two different amplitudes are used to represent 0 and 1. More than two levels can be used to represent more symbols. Similarly, with FSK (Frequency Shift Keying), two or more different tones are used. In the simplest form of PSK (Phase Shift Keying), the carrier wave systematically shifts 0 or 180 degrees at each symbol period. Because there are two phases, it is called BPSK (Binary Phase Shift Keying). ''Binary'' refers to the two symbols, not the symbols representing 2 bits. A better scheme that uses the channel bandwidth more efficiently is to use four shifts, e.g., 45, 135, 225, or 315 degrees, to transmit 2 bits of information per symbol. This version is called QPSK (Quadrature Phase Shift Keying).

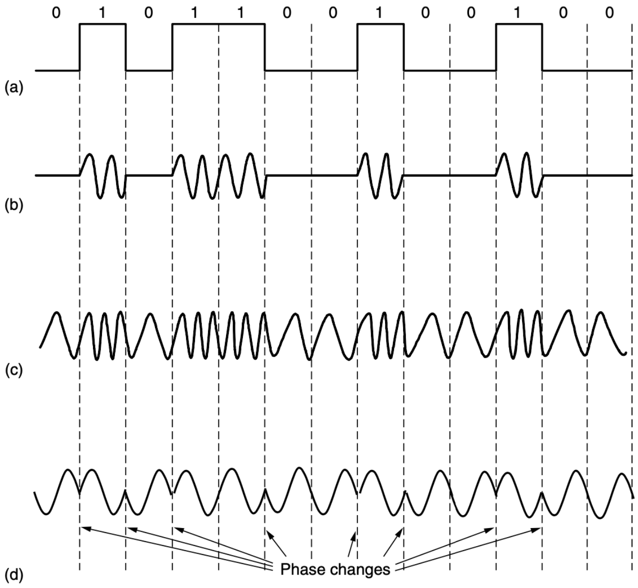


Figure 2-22. (a) A binary signal. (b) Amplitude shift keying. (c) Frequency shift keying. (d) Phase shift keying.

We often use a constellation diagram to represent amplitudes and phases. The amplitude of a dot is the distance from the origin. The figure (a) below is a representation of QPSK.

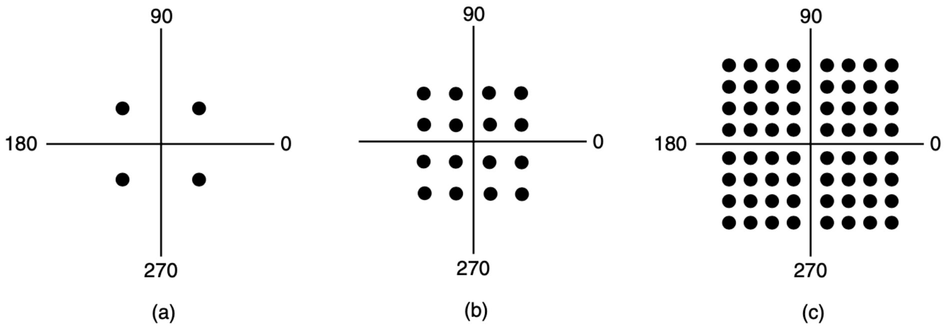


Figure 2-23. (a) QPSK. (b) QAM-16. (c) QAM-64.

We also see a modulation scheme with a denser constellation in figure (b). Sixteen combinations of amplitudes and phase are used, so the modulation scheme can be used to transmit 4 bits per symbol. It is called QAM-16, where QAM stands for Quadrature Amplitude Modulation. Figure (c) here is an even denser modulation scheme with 64 combinations, so 6 bits can be transmitted per symbol. It is called QAM-64.

ANALOG-TO-ANALOG CONVERSION

Analog-to-analog conversion can be accomplished in three ways: amplitude modulation (AM), frequency modulation (FM), and phase modulation (PM). FM and PM are usually categorized together.

In AM transmission, the carrier signal is modulated so that its amplitude varies with the changing amplitudes of the modulating signal. The frequency and phase of the carrier remain the same.

In FM transmission, the carrier signal frequency is modulated to follow the changing voltage level (amplitude) of the modulating signal. The peak amplitude and phase of the carrier signal remain constant, but as the amplitude of the information signal changes, the frequency of the carrier changes correspondingly.

Figure 5.16 *Amplitude modulation*

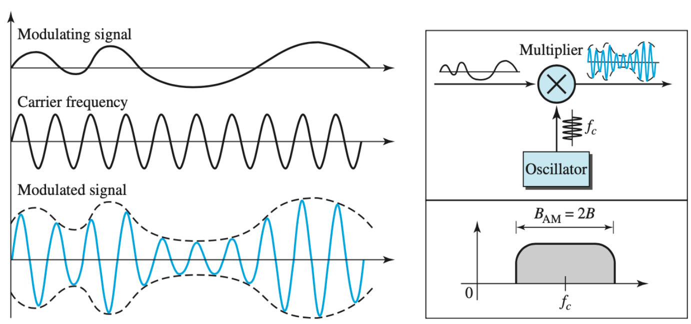
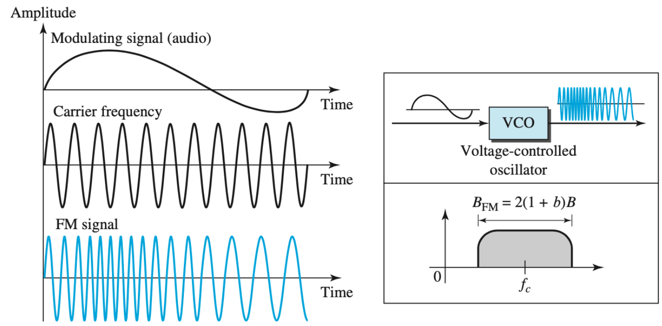


Figure 5.18 *Frequency modulation*



MULTIPLEXING

Multiplexing is the set of techniques that allow the simultaneous transmission of multiple signals across a single data link. As data and telecommunications use increases, so does traffic.

1. Frequency-Division Multiplexing

   Frequency-division multiplexing (FDM) is an analog technique that can be applied when the bandwidth of a link (in hertz) is greater than the combined bandwidths of the signals to be transmitted. Carrier frequencies are separated by sufficient bandwidth to accommodate the modulated signal. These bandwidth ranges are the channels through which the various signals travel. Channels can be separated by strips of unused bandwidth—guard bands—to prevent signals from overlapping.

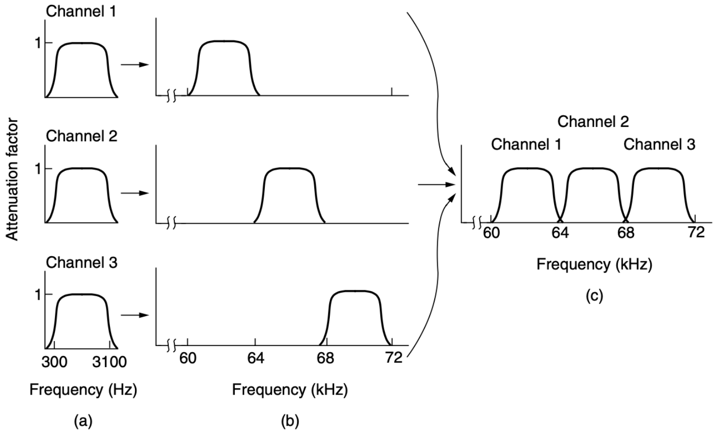


Figure 2-25. Frequency division multiplexing. (a) The original bandwidths. (b) The bandwidths raised in frequency. (c) The multiplexed channel.

2. Time Division Multiplexing

   An alternative to FDM is TDM (Time Division Multiplexing). Here, the users take turns (in a round-robin fashion), each periodically getting the entire bandwidth for a little time.

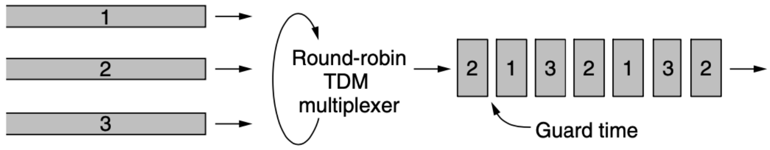


Figure 2-27. Time Division Multiplexing (TDM).

3. Code Division Multiplexing

   CDM (Code Division Multiplexing) is a form of *spread spectrum* (discussed next) communication in which a narrowband signal is spread out over a wider frequency band. This allows multiple signals from different users to share the same frequency band. It is commonly used for CDMA (Code Division Multiple Access).

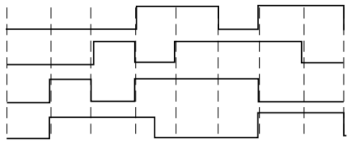
   Each station has its own unique chip sequence. Let us use the symbol S to indicate the m-chip vector for station S. All chip sequences are pairwise orthogonal, meaning that the normalized inner product of any two distinct chip sequences, S and T (written as S•T), is 0. Generate such orthogonal chip sequences using a method known as Walsh codes. In mathematical terms, the orthogonality of the chip sequences can be expressed as follows:

$$\mathbf{S} \bullet \mathbf{T} \equiv \frac{1}{m} \sum_{i=1}^{m} S_i T_i = 0$$

During each bit time, a station can transmit a 1 (by sending its chip sequence) or a 0 (by sending the negative of its chip sequence), or it can be silent and transmit nothing. We assume for now that all stations are synchronized in time, so all chip sequences begin at the same instant. When two or more stations transmit simultaneously, their bipolar sequences add linearly. Let us consider the below example. Here, we first list the assigned 8-dimensional chip sequences for four senders: A, B, C, and D.

A = (−1 −1 −1 +1 +1 −1 +1 +1)
B = (−1 −1 +1 −1 +1 +1 +1 −1)
C = (−1 +1 −1 +1 +1 +1 −1 −1)
D = (−1 +1 −1 −1 −1 −1 +1 −1)

(a)



(b)

$S_1 = C$ = (−1 +1 −1 +1 +1 +1 −1 −1)
$S_2 = B+C$ = (−2 0 0 0 +2 +2 0 −2)
$S_3 = A+\bar{B}$ = (0 0 −2 +2 0 −2 0 +2)
$S_4 = A+\bar{B}+C$ = (−1 +1 −3 +3 +1 −1 −1 +1)
$S_5 = A+B+C+D$ = (−4 0 −2 0 +2 0 +2 −2)
$S_6 = A+B+\bar{C}+D$ = (−2 −2 0 −2 0 −2 +4 0)

(c)

$S_1 \bullet C$ = [1+1−1+1+1+1−1−1]/8 = 1
$S_2 \bullet C$ = [2+0+0+0+2+2+0+2]/8 = 1
$S_3 \bullet C$ = [0+0+2+2+0−2+0−2]/8 = 0
$S_4 \bullet C$ = [1+1+3+3+1−1+1−1]/8 = 1
$S_5 \bullet C$ = [4+0+2+0+2+0−2+2]/8 = 1
$S_6 \bullet C$ = [2−2+0−2+0−2−4+0]/8 = −1

(d)

Figure 2-28. (a) Chip sequences for four stations. (b) Signals the sequences represent (c) Six examples of transmissions. (d) Recovery of station C's signal.

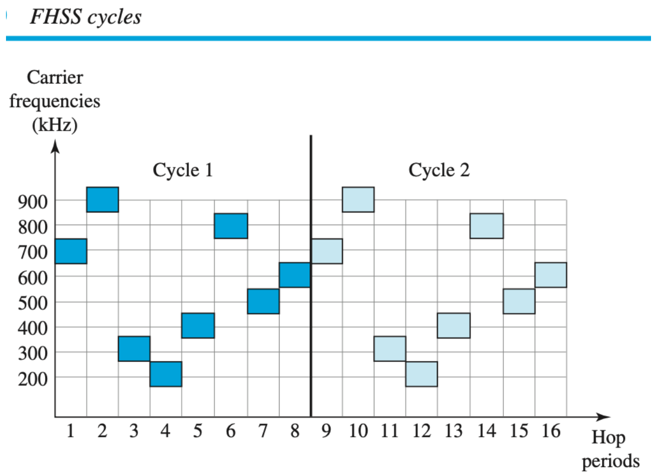
In the first example, C transmits a 1 bit, so we get C's chip sequence. In the second example, both B and C transmit 1 bit, so we get the sum of their bipolar chip sequences, namely:

$$(-1-1+1-1+1+1+1-1) + (-1+1-1+1+1+1-1-1) = (-2\ 0\ 0\ 0{+}2{+}2\ 0{-}2)$$

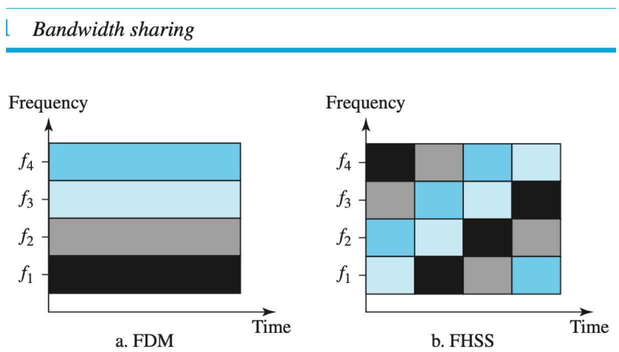
SPREAD SPECTRUM

1. Frequency Hopping Spread Spectrum

   The frequency hopping spread spectrum (FHSS) technique uses M different carrier frequencies that are modulated by the source signal. At one moment, the signal moderates one carrier frequency; at the next moment, the signal modulates another carrier frequency. Although the modulation uses one carrier frequency at a time, M frequencies are used in the long run.

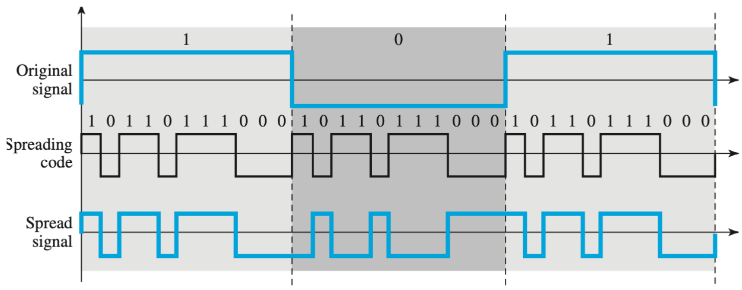


The diagram below shows how it is different from FDM. Each color represents a data from a different source.



2. Direct Sequence Spread Spectrum
   The direct sequence spread spectrum (DSSS) technique also expands the bandwidth of the original signal, but the process is different. In DSSS, we replace each data bit with n bits using a spreading code. In other words, each bit is assigned a code of n bits, called chips, where the chip rate is n times that of the data bit.

DSSS example



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