CWNA Guide to Wireless LANs, Third Edition

Chapter 3: Radio Frequency Fundamentals

Objectives

- Explain the basic principals of radio frequency (f) transmissions
- Describe the different types of analog and digital modulation
- List the units of measurement for radio frequency transmissions
- Describe how radio frequency waves behave and the impact of these behaviors on transmissions

Principles of Radio Frequency

- Understanding principles of radio wave transmission is important for:
  - Troubleshooting wireless LANs
  - Creating a context for understanding wireless terminology

What Are Electromagnetic Waves?

- **Electromagnetic wave:** Travels freely through space in all directions at speed of light
  - Consists of an electric field and a magnetic field that are perpendicular to each other

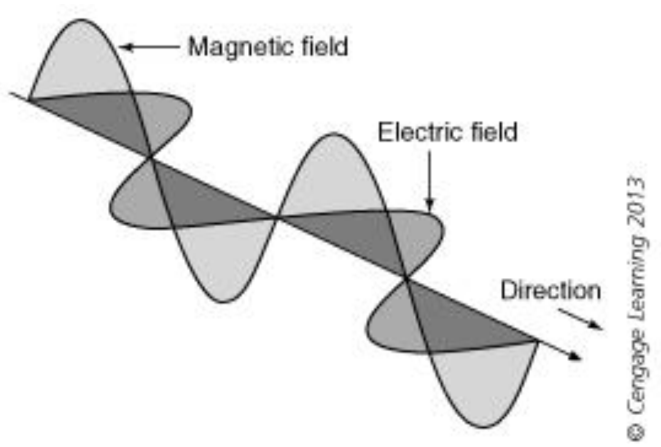


Figure 3-1 Electromagnetic wave

Electromagnetic Wave Characteristics

- Characteristics of electromagnetic waves:
  - **Continuous** - does not repeatedly start and stop
  - **Cycle -** When wave completes trip and returns back to starting point it has finished one cycle
- Cycles are illustrated by an up-and-down wave called an **oscillating signal** or **sine wave**
- All electromagnetic waves share the same four characteristics: wavelength, frequency, amplitude, and phase

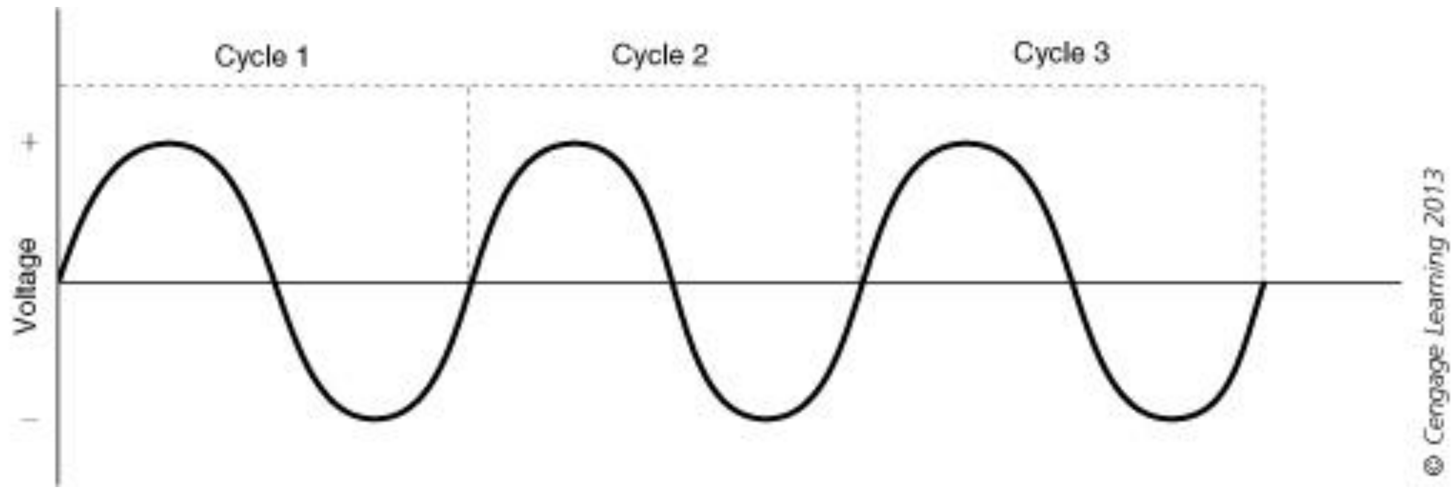


Figure 3-3 Sine wave

Wavelength

- Wavelength – distance between the wave's peaks
  - Can also be measured from anywhere in the wave as long as it is at the same point in each cycle

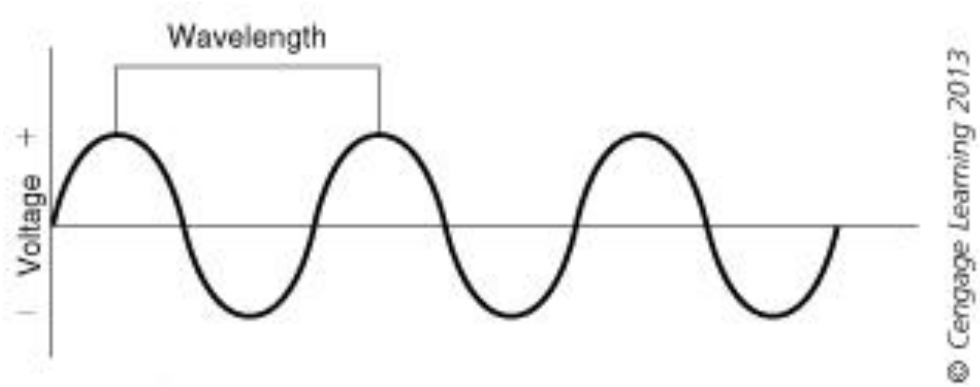


Figure 3-6 Wavelength

Frequency

- **Frequency:** Rate at which an event occurs
  - Number of times that a wave completes a cycle within a given amount of time
- **Hertz (Hz):** Cycles per second
  - **Kilohertz (KHz)** = thousand hertz (10^3 Hz)
  - **Megahertz (MHz)** = million hertz (10^6 Hz)
  - **Gigahertz (GHz)** = billion hertz (10^9 Hz)
  - **Terahertz (THz)** = billion hertz (10^{12} Hz)

Frequency

- Wavelength and frequency have an inverse relationship
  - The higher the frequency (f), the shorter the wavelength (λ) will be and the longer the wavelength, the lower the frequency.

$$\lambda = \frac{c}{f}$$

$c=3.\ 10^8$ m/s

c: speed of light

f: in Hertz (Hz)

λ: meters

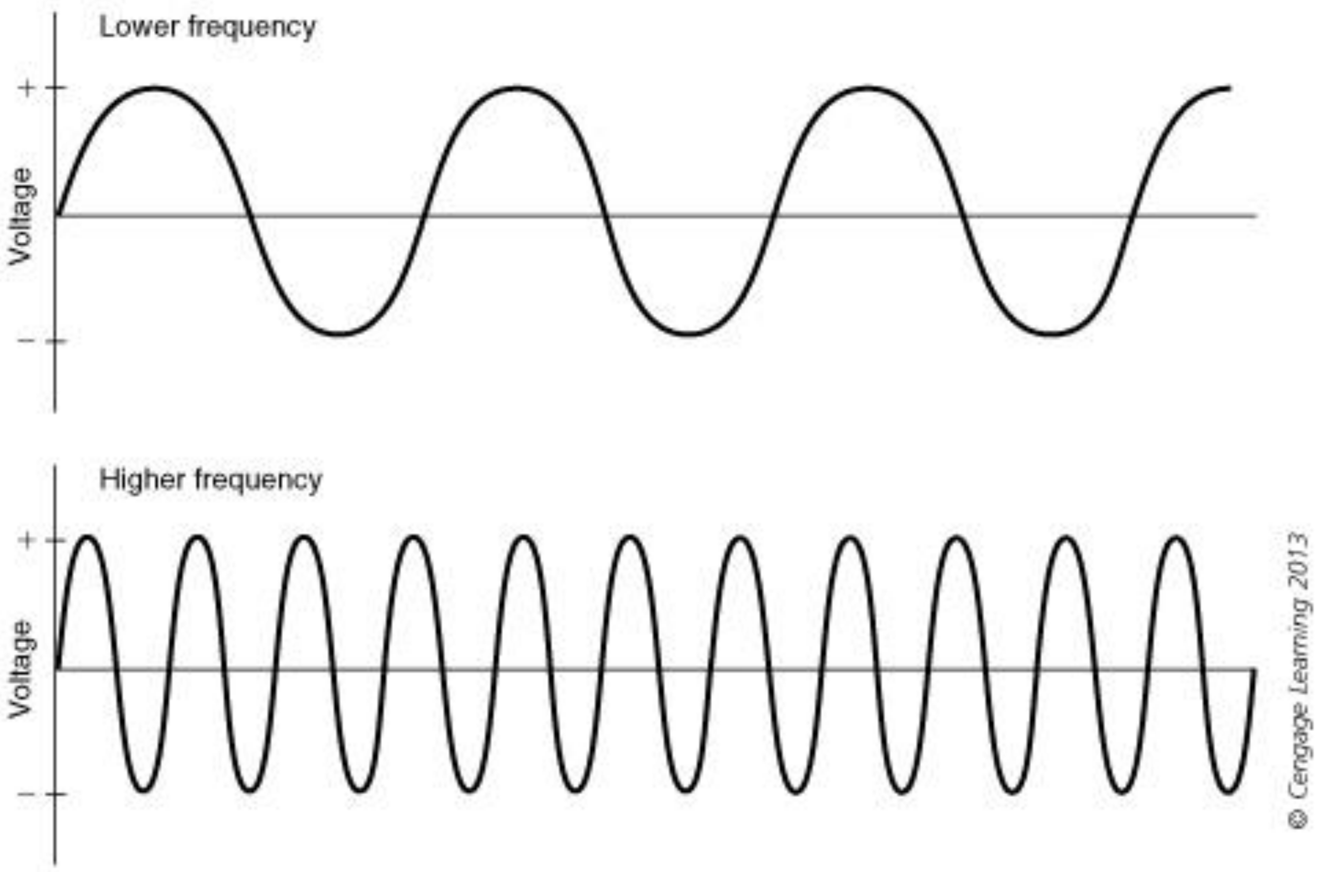


Figure 3-7 Lower and higher frequencies

Name	Abbreviation	Definition
Hertz	Hz	1 cycle per second
Kilohertz	KHz	1,000 cycles per second
Megahertz	MHz	1,000,000 cycles per second
Gigahertz	GHz	1,000,000,000 cycles per second

Table 3-1 Hertz abbreviations

Amplitude

- **Amplitude**: the magnitude of change of the wave
  - Is measured by how high or how deep the wave is
  - Is essentially a measure of the strength of an electromagnetic wave's signal
- Different types of transmissions require different signal strengths

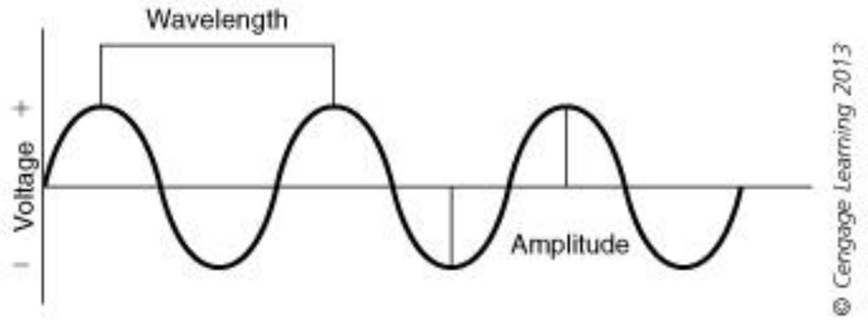


Figure 3-8 Amplitude

Phase

- **Phase**: the relationship between at least two signals that share the same frequency yet have different starting points
  - Two signals that have the same peaks and valleys are called **in phase**
  - If peaks and valleys do not match they are **out of phase**
  - If two signals are the complete opposite of each other the first signal is in phase
    - Second signal is **180 degrees out of phase**

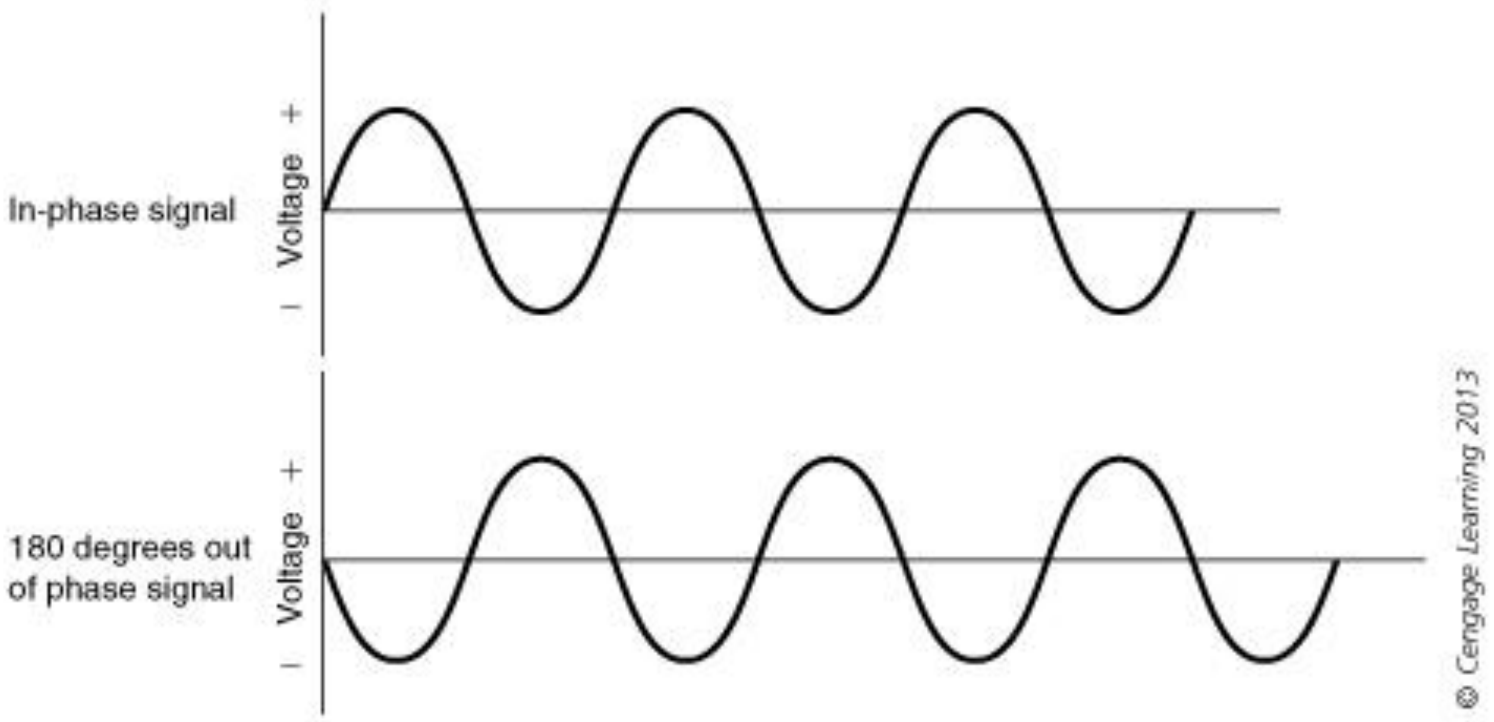


Figure 3-11 In phase and 180 degrees out of phase

The Electromagnetic Spectrum

- Electromagnetic spectrum: range of all electromagnetic radiation
  - Further subdivided into 450 different sections or bands

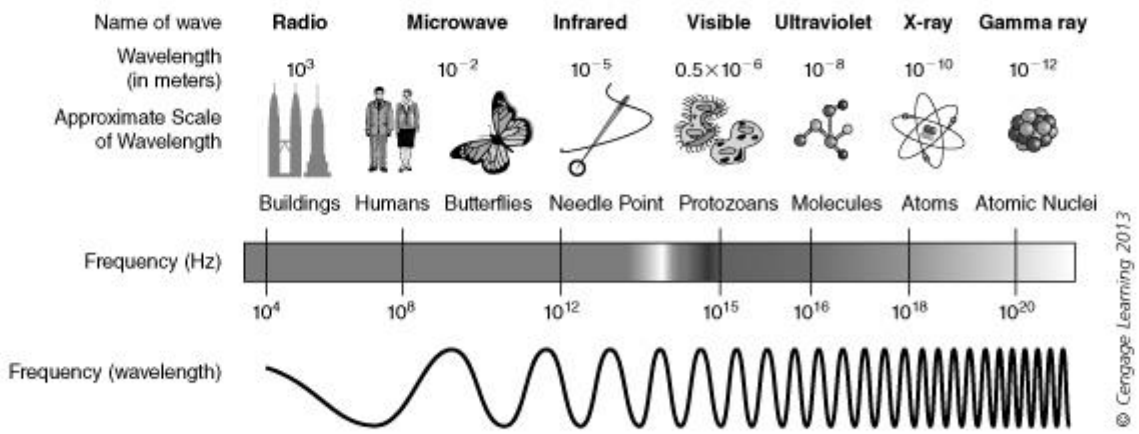


Figure 3-12 Electromagnetic spectrum

Name	Description	How They Are Used
Radio	Radio waves have the longest wavelengths in the electromagnetic spectrum, ranging from longer than a soccer field to as short as the length of a soccer ball.	Radio waves can carry music to car radios, signals for television, and voice and data for cellular phones.
Microwave	Microwaves have wavelengths that can be measured in centimeters; longer microwaves of almost one foot in length are used to heat food in a microwave oven.	Microwaves are good for transmitting information over distances because microwave energy can penetrate haze, light rain and snow, clouds, and smoke.
Infrared	Infrared light has a range of wavelengths, from "near infrared" light with wavelengths that are microscopic to "far infrared" with wavelengths about the size of a pin head.	Far infrared waves are thermal, which means they can carry heat; for example special lamps that emit thermal infrared waves are often used in fast food restaurants, while near infrared waves are used by television remote controls.
Visible	Visible light waves are the only electromagnetic waves that can be seen by humans and appear as the colors of the rainbow.	Each color has a different wavelength, with red the longest wavelength and violet the shortest wavelength.
Ultraviolet	Ultraviolet (UV) light, which has shorter wavelengths than visible light, are invisible to the human eye, although some insects can see it.	The sun emits light at all the different wavelengths in electromagnetic spectrum, but ultraviolet waves are responsible for causing sunburns.
X-ray	X-rays have smaller wavelengths and thus higher energy than ultraviolet waves; usually X-rays are referred to in terms of their energy rather than wavelength.	The earth's atmosphere is thick enough that virtually no X-rays are able to penetrate from outer space all the way to the earth's surface.
Gamma ray	Gamma rays have the smallest wavelengths and the most energy of any other wave in the electromagnetic spectrum.	Gamma rays are generated by radioactive atoms and in nuclear explosions and can be used to kill cancerous cells.

Table 3-2 Electromagnetic spectrum properties

The Electromagnetic Spectrum

- A license is normally required from the FCC to send and receive via a specific frequency
  - **Unlicensed bands**: parts of the radio spectrum that are available nationwide to all users without requiring a license
  - FCC does impose power limits on devices using the unregulated bands (reduces their range)
- Unlicensed National Information Infrastructure (UNII) band: intended for devices that provide short-range, high-speed wireless digital communications

Band	Frequency	Common Uses
Very Low Frequency (VLF)	10 KHz to 30 KHz	Maritime ship-to-shore
Low Frequency (LF)	30 KHz to 300 KHz	Aircraft beaconing signals
Medium Frequency (MF)	300 KHz to 3 MHz	AM radio
High Frequency (HF)	3 MHz to 30 MHz	Shortwave radio, CB radio
Very High Frequency (VHF)	30 MHz to 144 MHz 144 MHz to 174 MHz 174 MHz to 328.6 MHz	TV stations 2–6, FM radio Taxi radios TV stations 7–13
Ultra High Frequency (UHF)	328.6 MHz to 806 MHz 806 MHz to 960 MHz 960 MHz to 2.3 GHz 2.3 GHz to 2.9 GHz	Public safety Cellular telephones Air traffic control radar Wireless LANs
Super High Frequency (SHF)	2.9 GHz to 30 GHz	Wireless LANs
Extremely High Frequency (EHF)	30 GHz and above	Radio astronomy

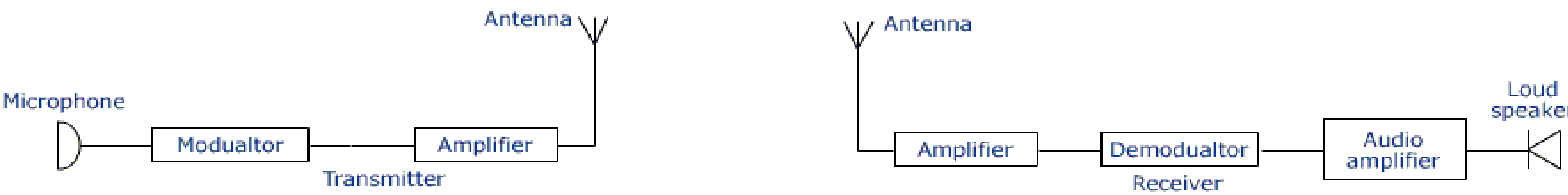
Table 3-3 Common radio frequency bands

Unlicensed Band	Frequency	Total Bandwidth	Common Uses
Industrial, Scientific and Medical (ISM)	902–928 MHz 2.4–2.4835 GHz 5.725–5.85 GHz	234.5 MHz	Cordless phones, WLANs, Wireless Public Branch Exchanges
Unlicensed Personal Communications Services	1910–1930 MHz 2390–2400 MHz	30 MHz	Wireless Public Branch Exchanges
Unlicensed National Information Infrastructure (UNII)	5.15–5.25 GHz 5.25–5.35 GHz 5.725–5.825 GHz	300 MHz	WLANs, Wireless Public Branch Exchanges, campus applications, long outdoor links
Millimeter Wave	59–64 GHz	5 GHz	Home networking applications

Table 3-4 Unlicensed bands

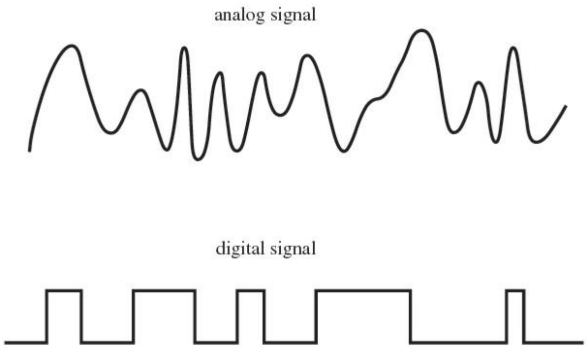
Radio Frequency Modulation

- In order for an electromagnetic wave to transmit information it must be modified
  - Modification is called **modulation** or **keying**
- An electromagnetic wave that has been modified in order to carry information is a **carrier**
  - Also called **carrier wave** or **carrier signal**
- Modulations can be performed on either analog or digital transmissions



Analog Modulation

- **Analog signal**: continuous signal with no breaks
- **Digital signal**: discrete signal with breaks

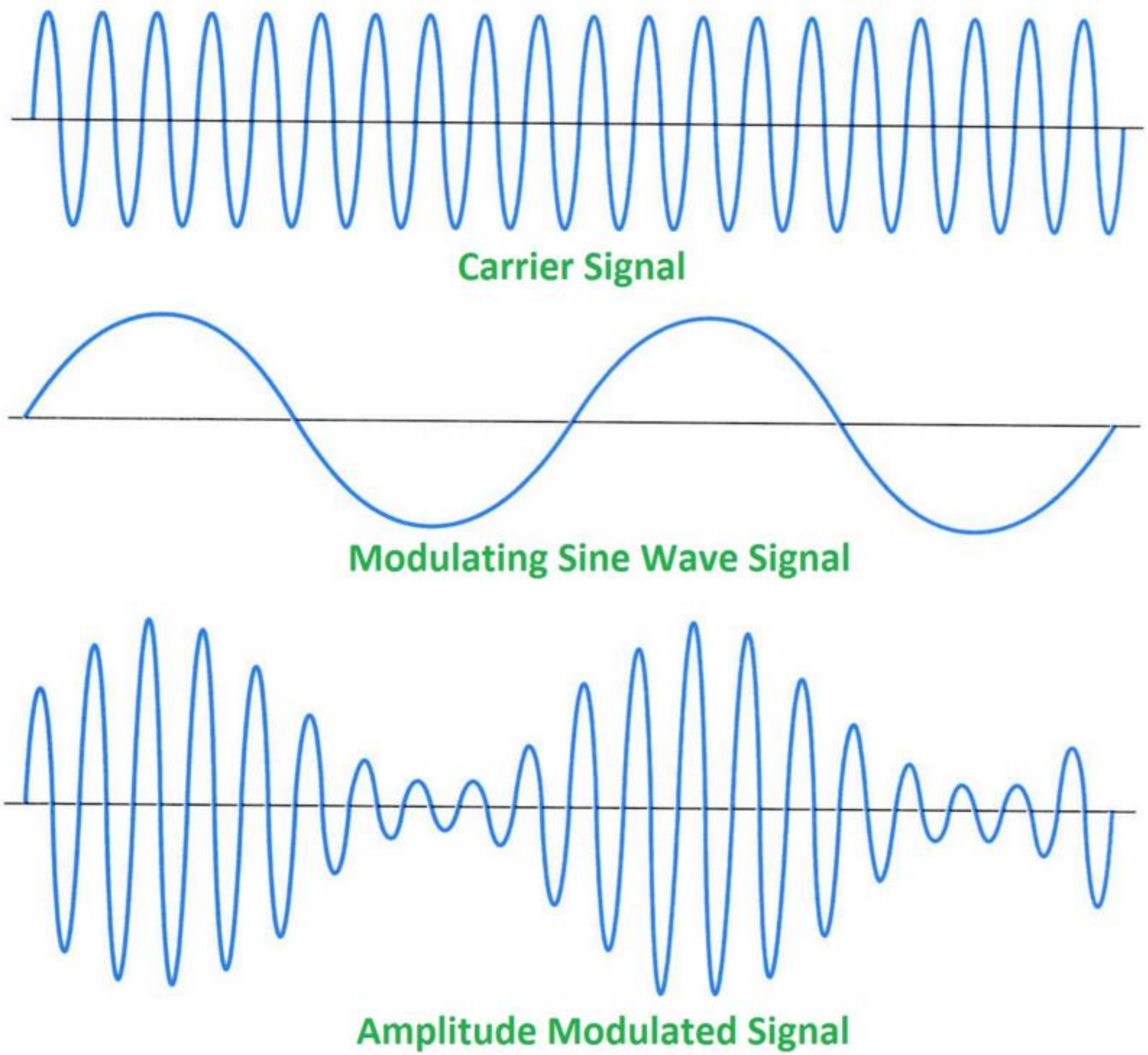


- **Amplitude modulation (AM):** Changes amplitude so that highest peaks of carrier wave represent 1 bit while lower waves represent 0 bit

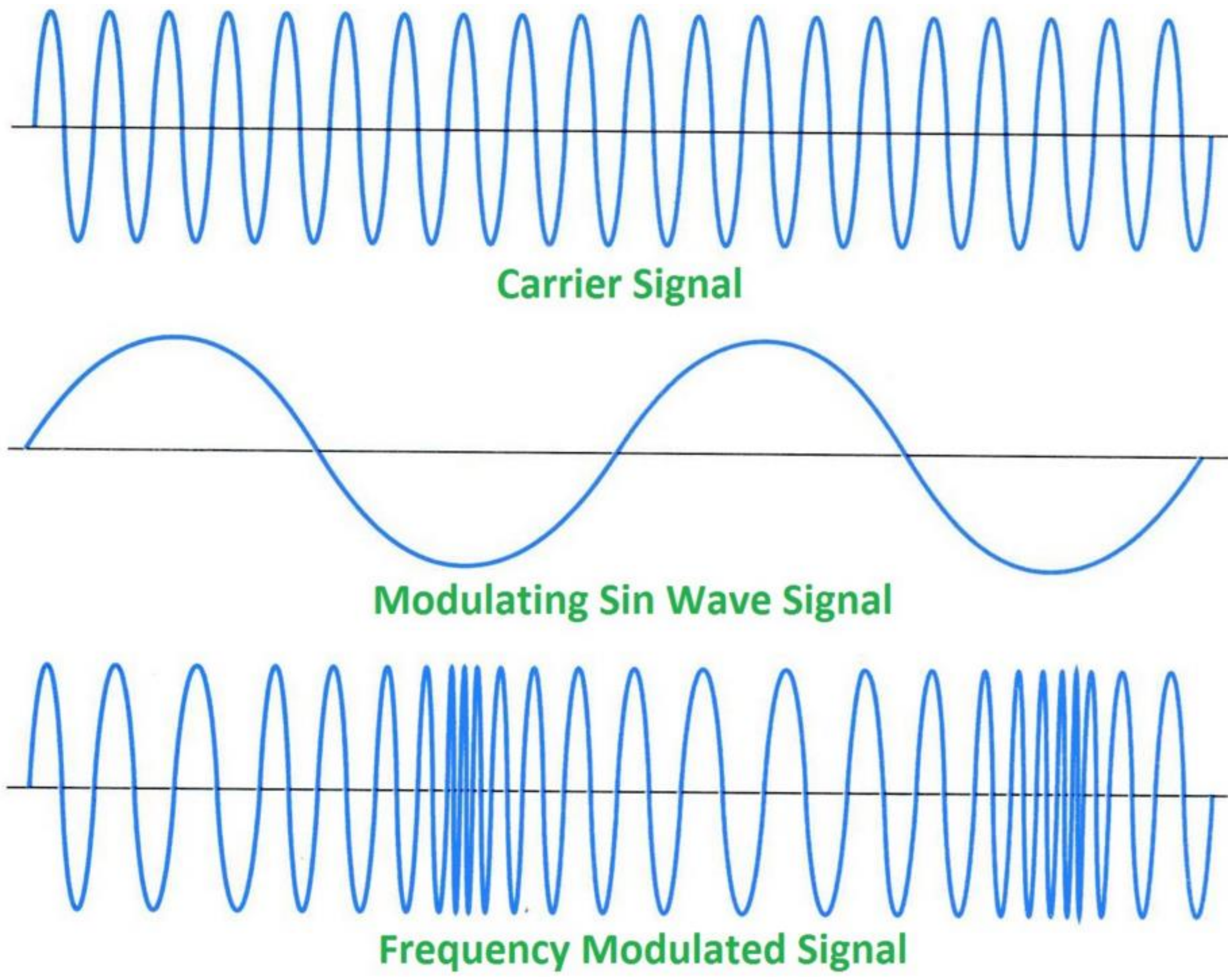
- **Frequency modulation (FM):** Changes number of waves representing one cycle
  - Number of waves to represent 1 bit more than number of waves to represent 0 bit

- **Phase modulation (PM):** Changes starting point of cycle
  - When bits change from 1 to 0 bit or vice versa

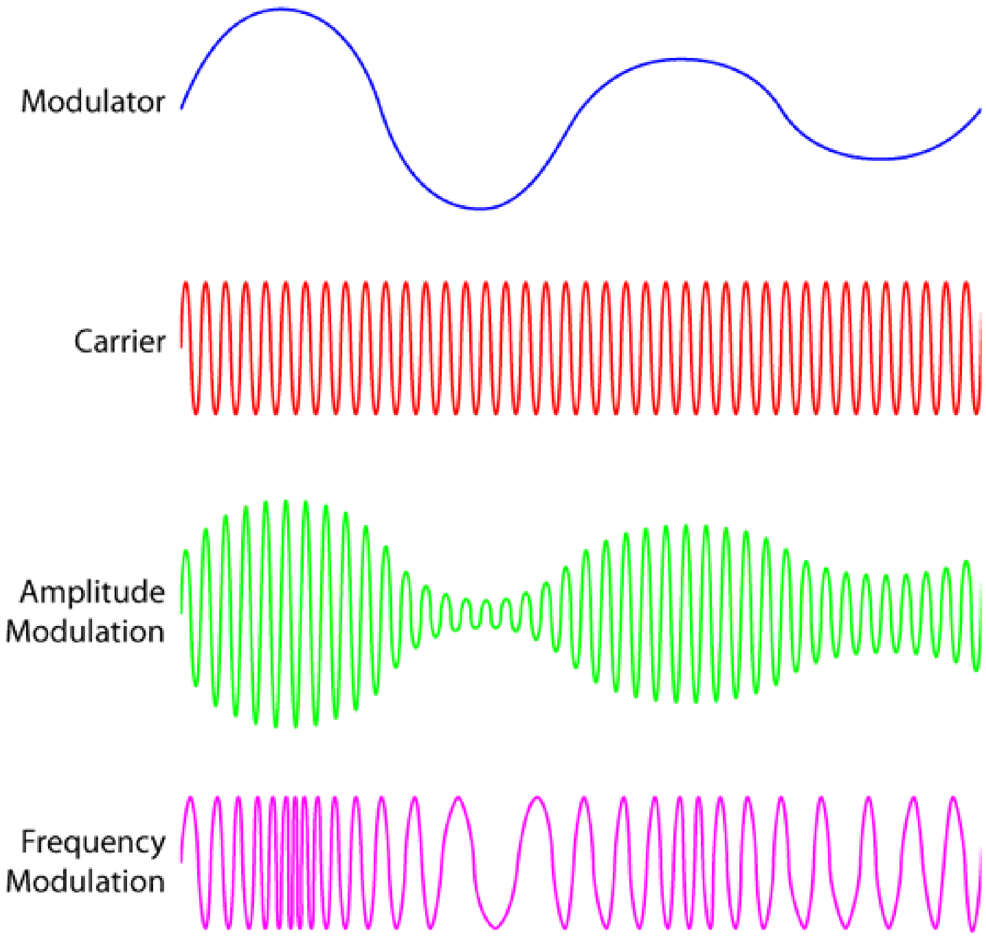
Amplitude Modulation (AM)

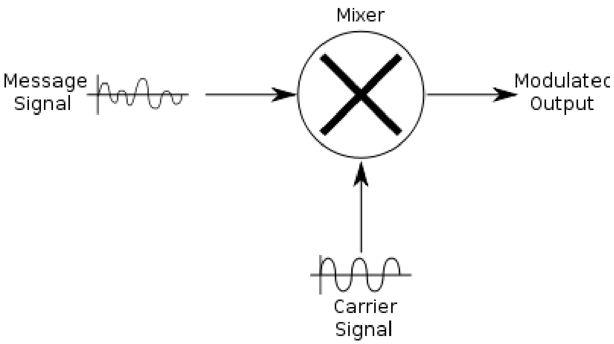


Frequency Modulation (FM)



Radio Frequency Modulation (AM-FM)





https://en.wikipedia.org/wiki/Modulation#/media/File:Amfm3-en-de.gif

http://mri-q.com/signal-squiggles.html

https://www.youtube.com/watch?v=_5JyiFWLn-w

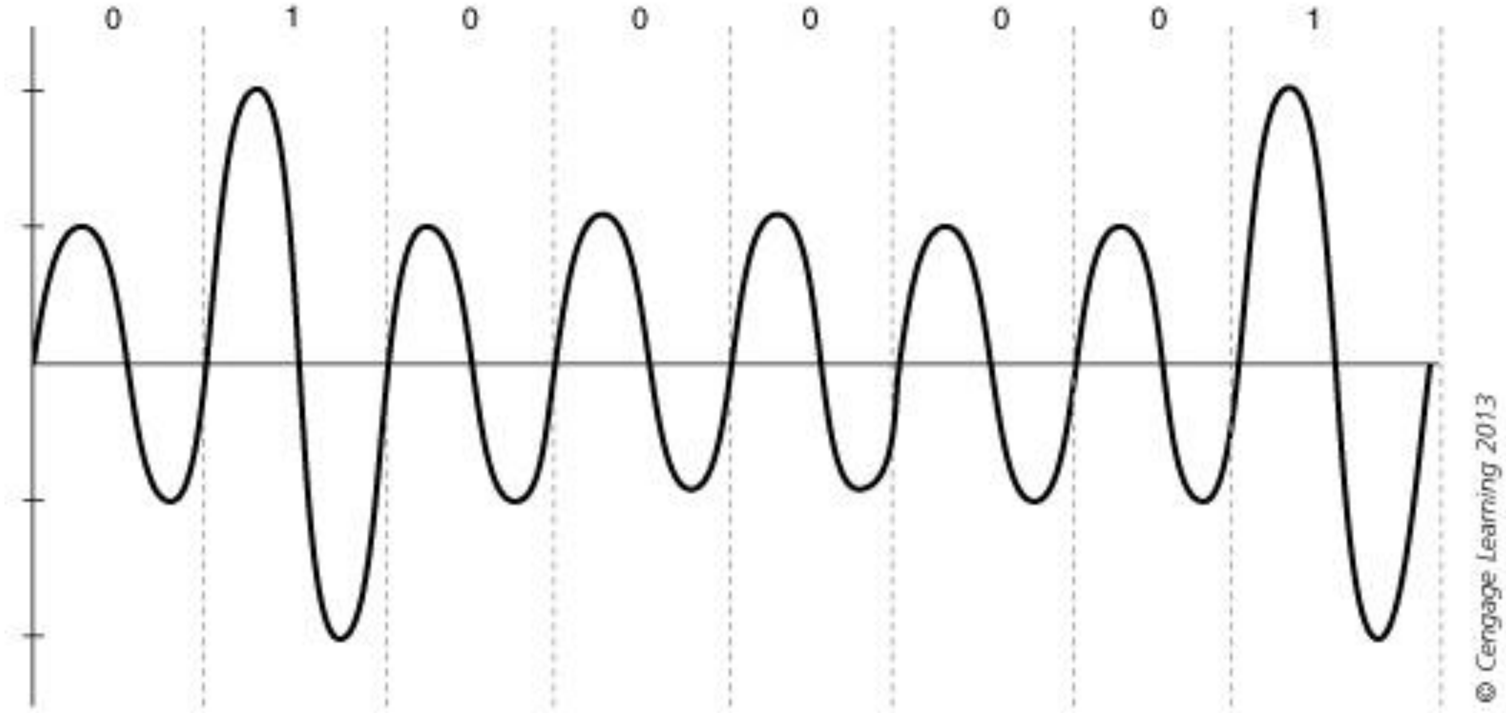


Figure 3-13 Amplitude modulation (AM)

https://www.youtube.com/watch?v=SmW4z76KgNQ

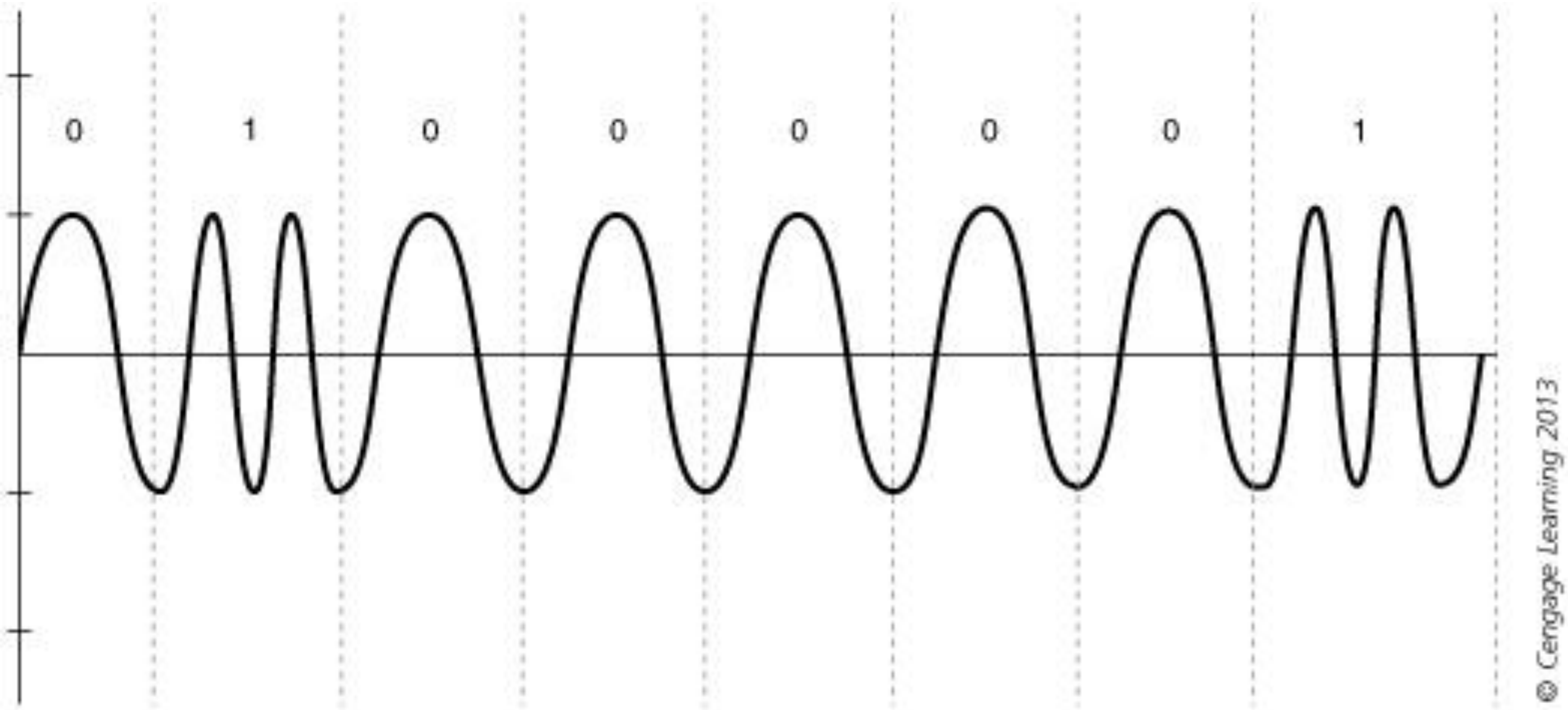
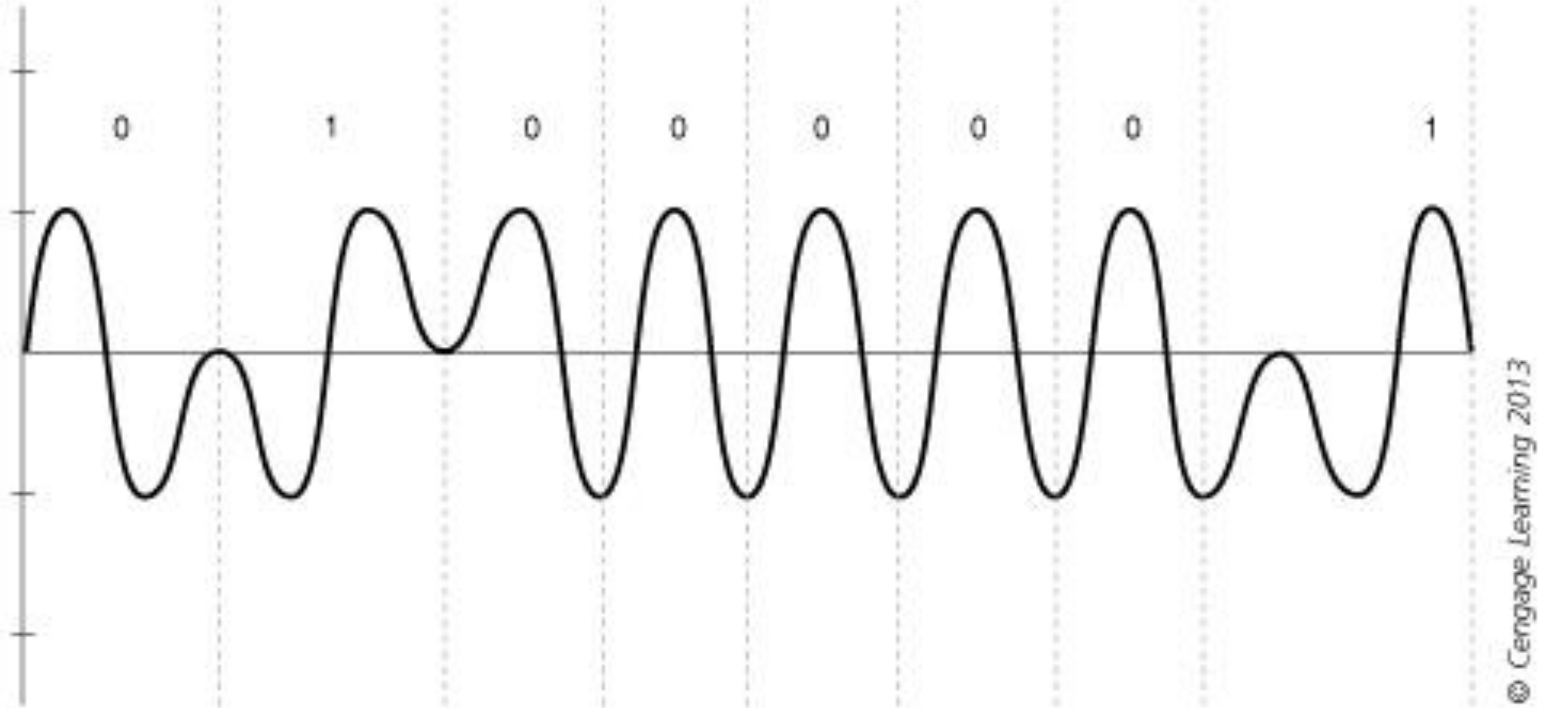


Figure 3-14 Frequency modulation (FM)



https://www.youtube.com/watch?v=D65KXwfDs3s

Figure 3-15 Phase modulation (PM)

Digital Modulation

- Digital signal: consists of data that is discrete or separate (unlike analog which is continuous)
- Advantages over analog modulation:
  - Better use of bandwidth
  - Requires less power
  - Better handling of interference from other signals
  - Error-correcting techniques more compatible with other digital systems
- Uses same three basic types of modulation as analog

Digital Modulation

- **Amplitude shift keying (ASK)**: similar to amplitude modulation
  - Instead of both a 1 bit and a 0 bit having a carrier signal, the ASK 1 bit has a carrier signal and a 0 bit has no signal
- **Frequency shift keying (FSK):** changes the frequency of the carrier signal
- **Phase shift keying (PSK)**: similar to phase modulation
  - PSK signal starts and stops because it is a binary signal

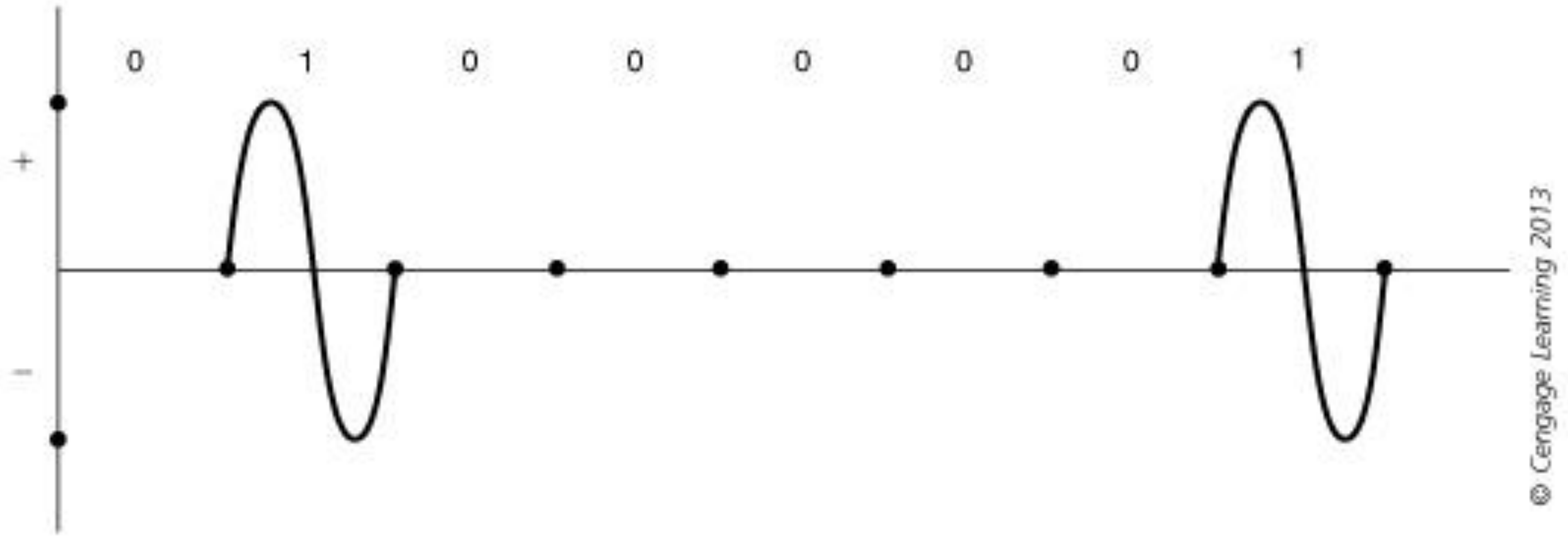
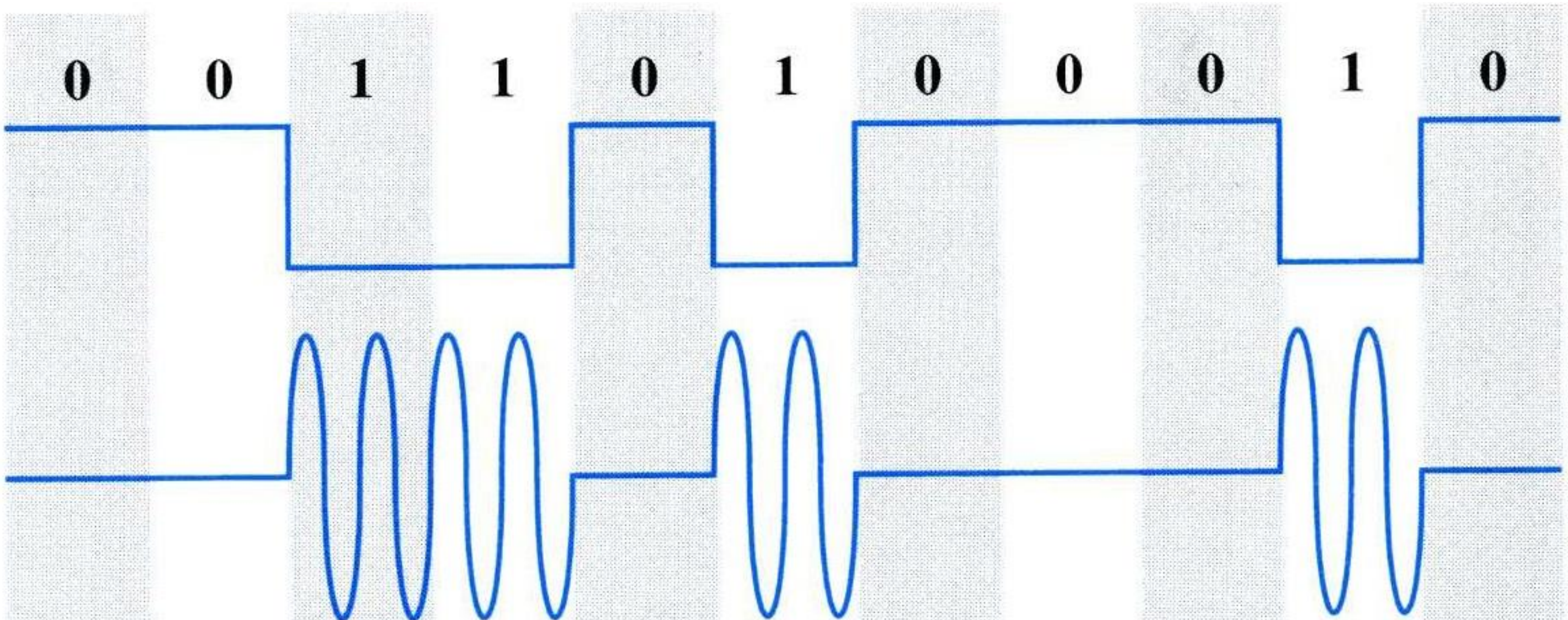


Figure 3-16 Amplitude shift keying (ASK)



Amplitude Shift Keying (ASK)

Two Amplitude Levels to represent 0 & 1

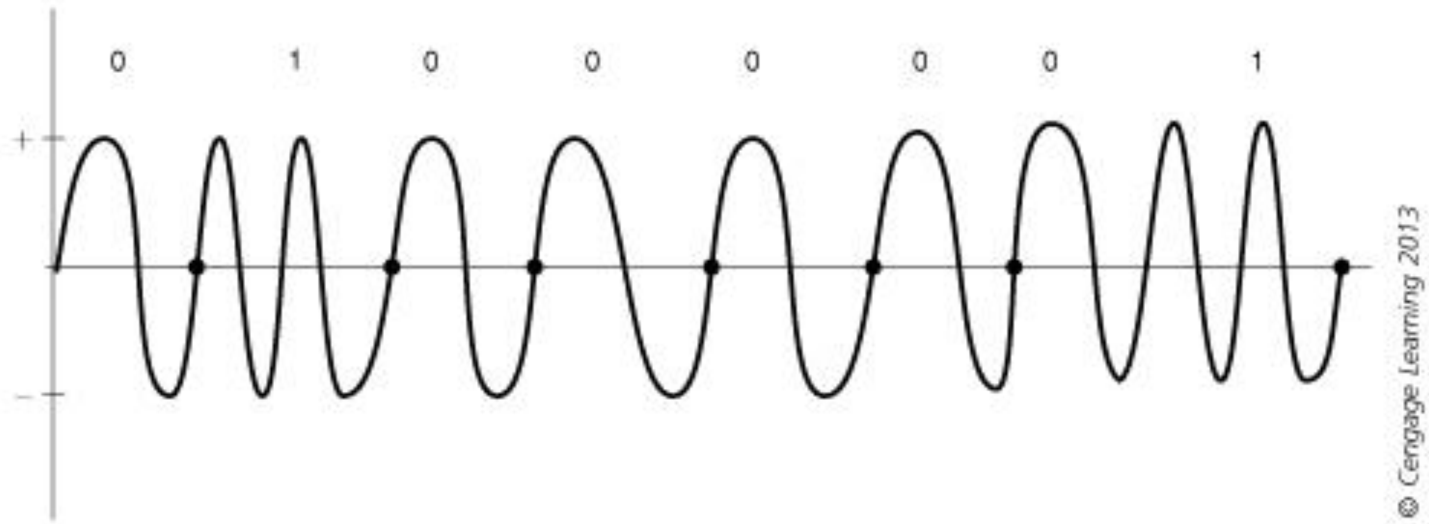
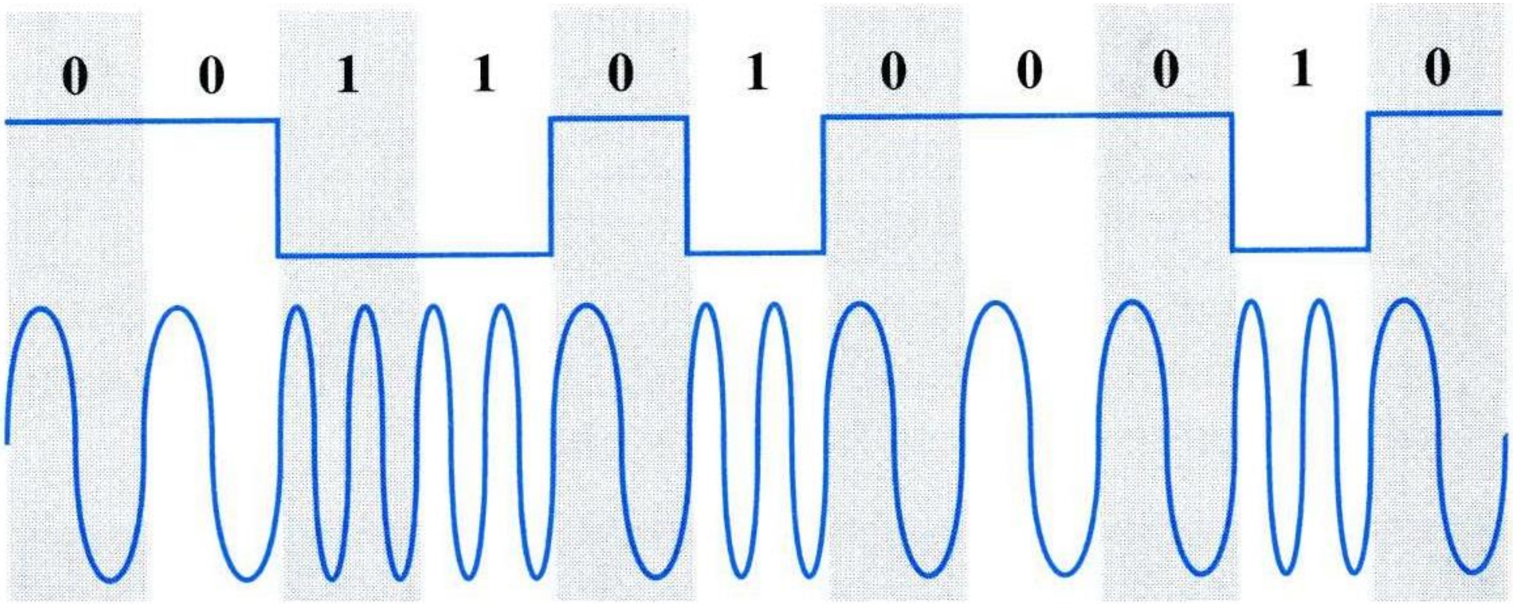


Figure 3-17 Frequency shift keying (FSK)



Frequency Shift Keying (FSK)

Two frequencies to represent 0 & 1

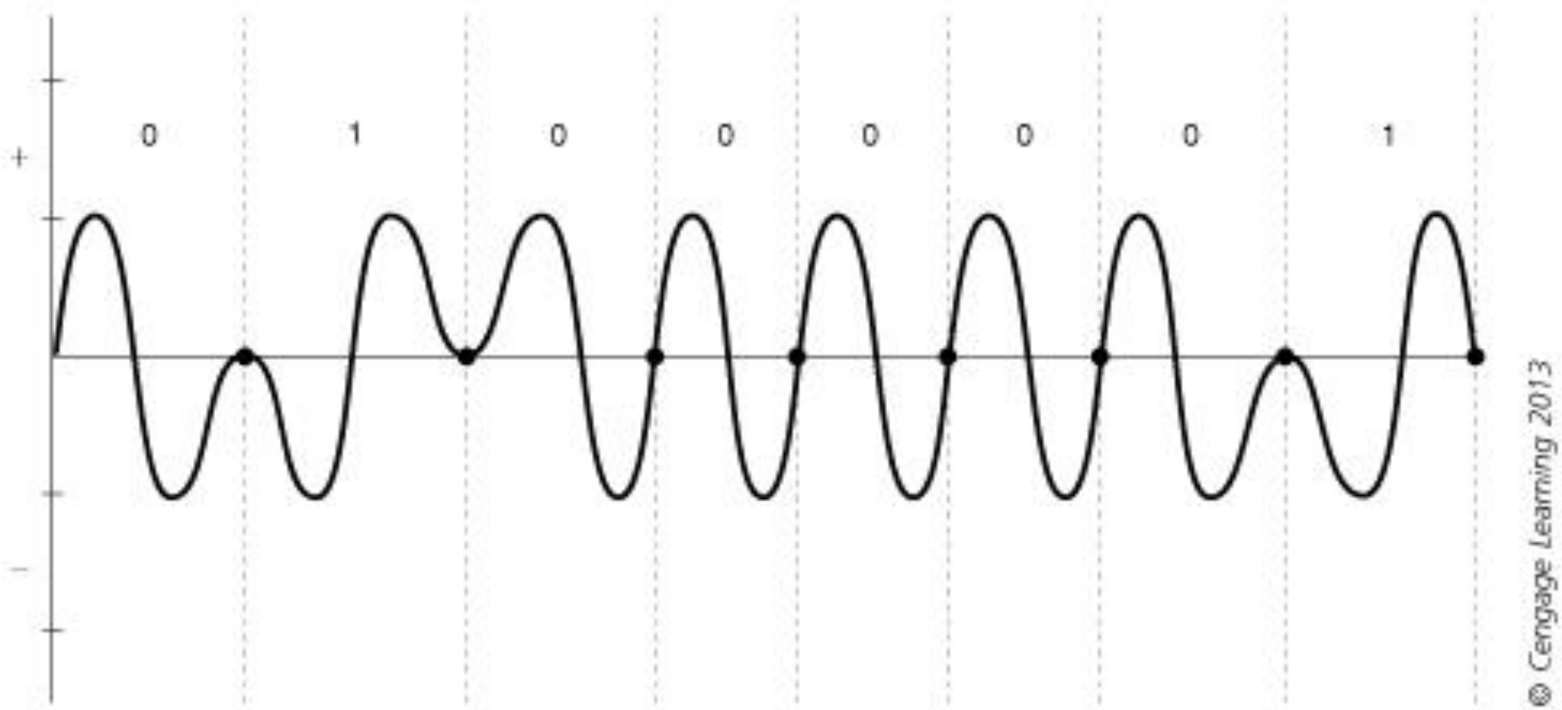
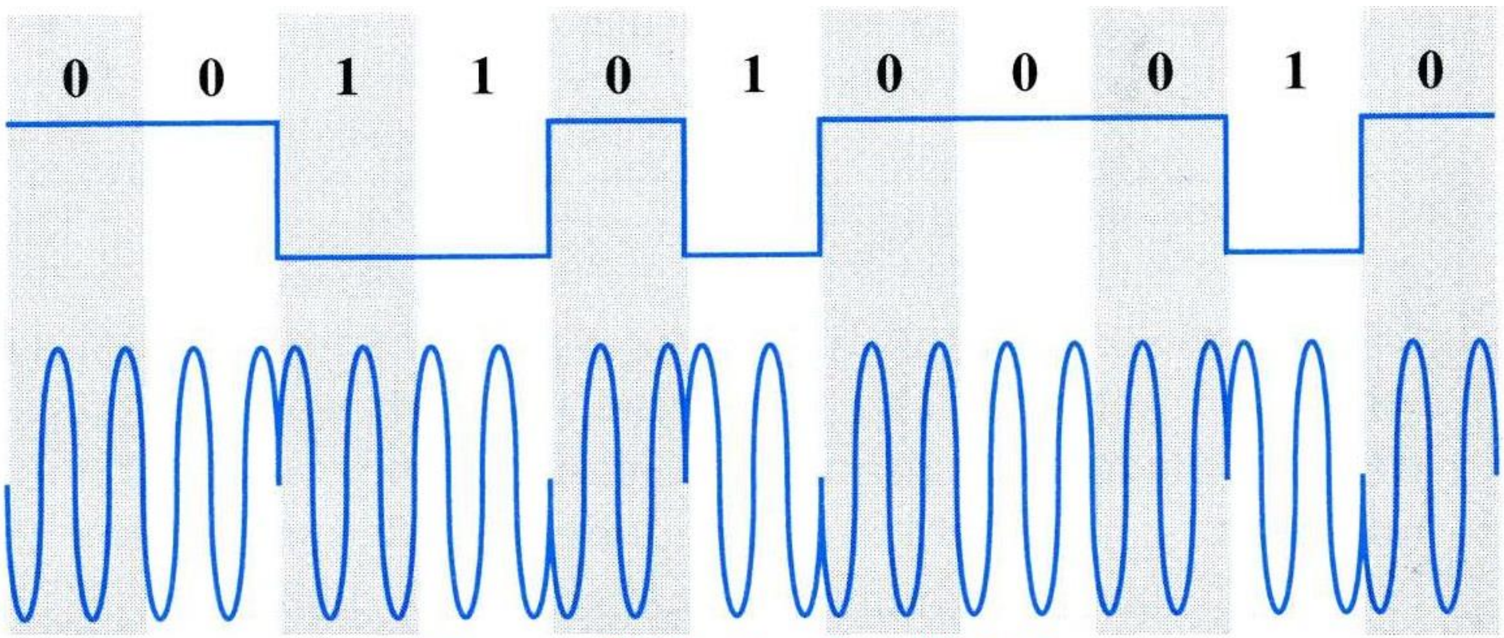


Figure 3-18 Phase shift keying (PSK)



Phase Shift Keying (PSK)

Or called BPSK, uses two phases to represent 0 & 1

RF Signal Strength Measurements

- Four units of measurements are used to represent RF signal strength:
  - mW (milliwatts)
  - dBm (decibel milliwatts)
  - RSSI (Receive Signal Strength Indicator)
  - Percentage

Milliwatt (mW)

- Voltage (V): electrical pressure on a wire and is measured in volts
- Current (I): rate of electrical flow and is measured in amperes or amps
- Resistance (R): Impedance of electrical flow and is measured in ohms
- Electrical power (P): amount of energy and is measured in watts (W)
  - A watt is a basic unit of power of 1 amp of current that flows at 1 volt
  - Milliwatt (mW) is one thousandth of a watt of power

Electrical term	Abbreviation	Description	Garden Hose Analogy	Unit of Measurement
Voltage	V	Electrical pressure on wire	Water pressure	Volts
Current	I	Rate of electrical flow	Water flow rate	Amperes (amps)
Resistance	R	Impedance of electrical flow	Diameter of hose	Ohms
Electrical power	P	Amount of energy	Total amount of water coming out of hose	Watts

Table 3-5 Electrical terminology

Decibel Milliwatt (dBm)

- RF power measured by two units on two scales:
  - Linear scale:
    - Using **milliwatts (mW)**
    - Reference point is zero
    - Does not reveal gain or loss in relation to whole
  - Relative scale:
    - Reference point is the measurement itself
    - Often use logarithms
    - Measured in **decibels (dB)**
- The reference point that relates the (dB) scale to the linear milliwatt scale is known as **decibel milliwatt** **(dBm)**

Decibel Milliwatt (dBm)

$$Power\ (in\ dB) = 10\ log_{10} \frac{P}{1\ (W)}$$

$$Power\ (in\ dBm) = 10\ log_{10} \frac{P}{1\ (mW)}$$

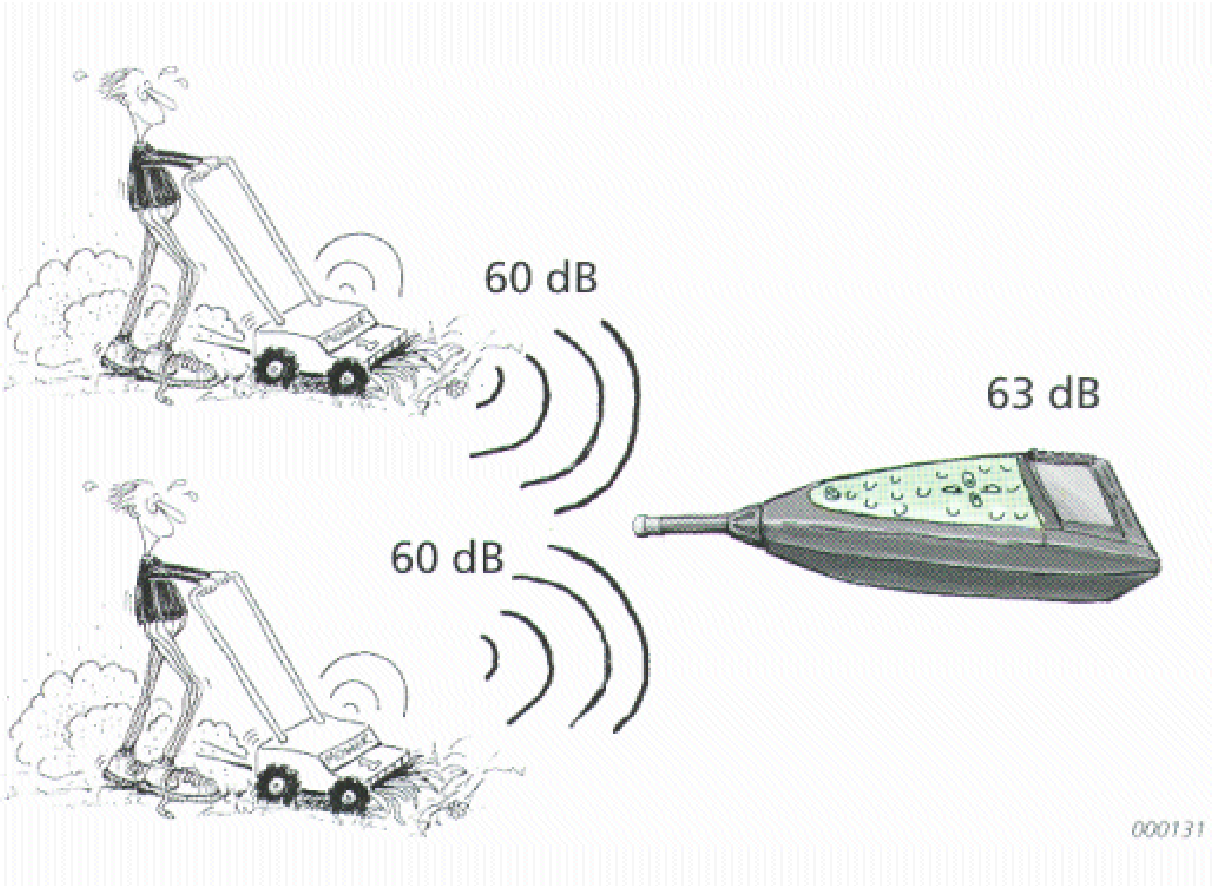
mW	Watts	dBm
0.01	0.00001	-20.0
0.1	0.0001	-10.0
1	0.001	0.0
2	0.002	3.0
3	0.003	4.8
4	0.004	6.0
5	0.005	7.0
6	0.006	7.8
7	0.007	8.5
8	0.008	9.0
9	0.009	9.5
10	0.01	10.0
100	0.1	20.0
200	0.2	23.0
300	0.3	24.8
400	0.4	26.0
500	0.5	27.0
600	0.6	27.8
700	0.7	28.5
800	0.8	29.0
900	0.9	29.5
1000	1	30.0

Decibel Milliwatt (dBm)

- Because dB and mW use different scales (linear vs. relative), a conversion is necessary when moving between the two
- A shortcut for calculating the increase of these RF values is known as the 10's and 3's Rules of RF Math
  - A decrease of 3 dBm yields roughly half the original value and an increase of 3 dBm yields roughly twice the original value
  - See Table 3-7 on the next slide

Rule	Explanation	Percentage of Power Lost/ Gained	Current Power Level	Example
−3 dB	Half the watt value	50% lost	Half of original	100 mW − 3 dB = 50 mW
+3 db	Double the watt value	100% gained	Double the original	10 mW + 3 dB = 20 mW
−10 dB	Decrease watt value to one tenth of original	90% lost	One-tenth of original	300 mW − 10 dB = 30 mW
+10 dB	Increase the watt value by 10-fold	1,000% gained	Ten times the original	10 mW + 10 dB = 100 mW

Table 3-7 The 10’s and 3’s Rules of RF Math


60 dB
63 dB
60 dB
000131

Receive Signal Strength Indicator (RSSI)

- **RSSI**: a mechanism by which RF signal strength can be measured by the circuitry on a wireless NIC
  - Value was intended for internal use by the wireless NIC
  - Example – a wireless NIC can check the RSSI value to:
    - determine if it is clear to send its transmission
    - Determine if the user is roaming beyond the range of a particular AP

Receive Signal Strength Indicator (RSSI)

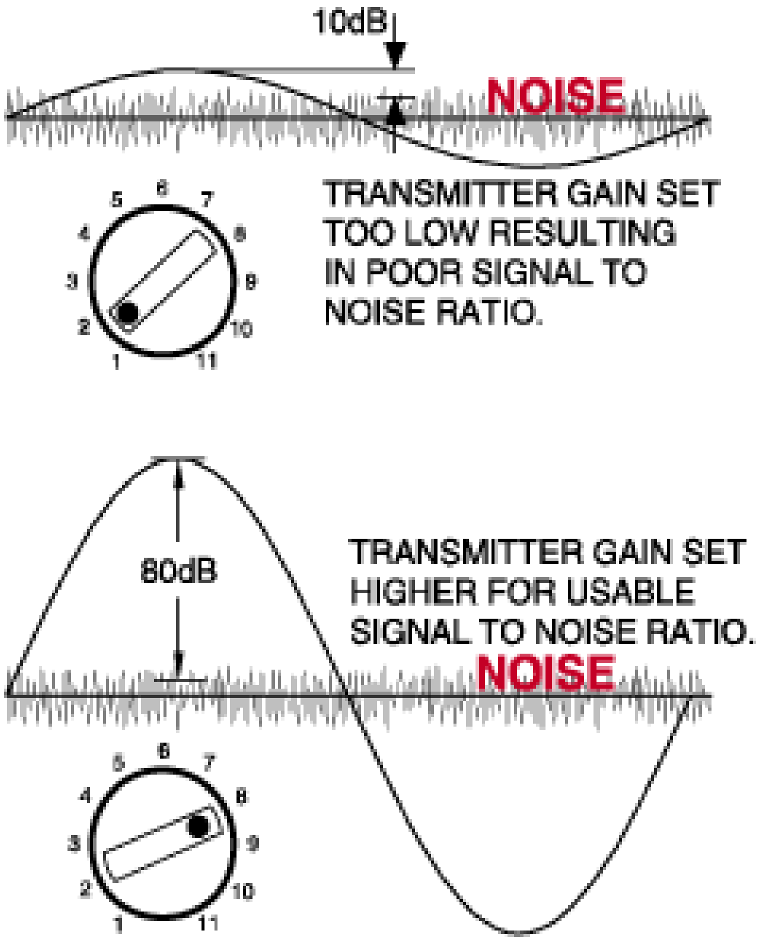
- RSSI should not be relied upon as a valid indicator of RF signal strength for three reasons:
  - RSSI was not intended to be used in that way
  - Each vendor may implement RSSI differently
    - There is no specified accuracy
  - All possible energy levels may not be represented by the integer set of RSSI value

Percentage

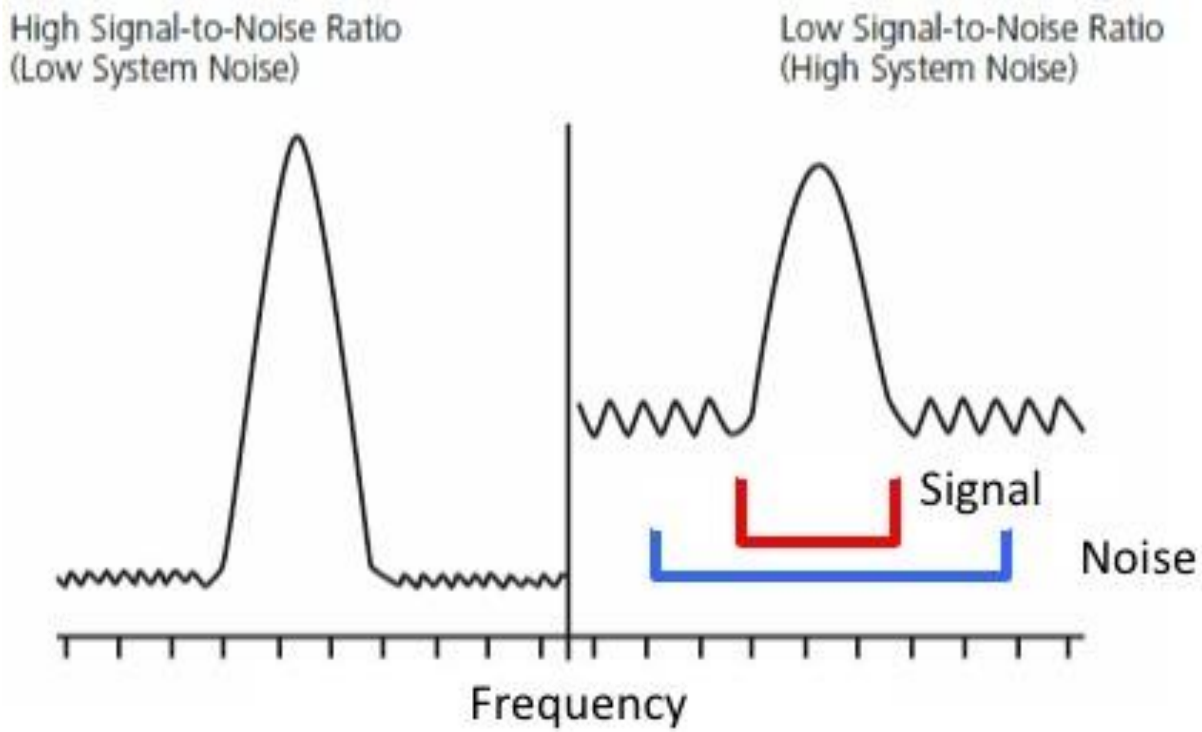
- Percentage is used to avoid inaccuracies of using RSSI as a basis for RF signal strength

- **Percentage**: represents the RSSI for a particular packet divided by the maximum RSSI value, then multiplied by 100

Signal-to-Noise Ratio



Signal-to-Noise Ratio



Signal-to-Noise Ratio

- **Noise**: unwanted interference that impacts the RF signal
- **Signal-to-noise ratio (SNR):** desired signal to undesired signal (noise) in the average power level of a transmission (given as dB)
- How SNR values relate to WLAN performance:
  - Over 40 dB = Excellent signal (5 bars)
  - 25 dB-40 dB = Very good signal (3-4 bars)
  - 15 dB-25 dB =Low signal (2 bars)
  - 10 dB-15 dB = Very low signal (1 bar)
  - Less than 10 dB = No signal (0 bar)

Radio Frequency Behavior

- RF signal behavior has an impact upon the speed of a transmission and distance achieved between two devices
  - Classified as propagation behaviors

Propagation Behaviors

- Common misconception: an RF signal goes out from an antenna in a single signal that takes a direct path to a receiver
- Incorrect in two ways:
  - There is not just one RF signal – multiple copies may reach the receiver (known as multipath)
  - Signal may "bounce" off of walls and other objects
    - **Wave propagation**: the way in which the signal travels
- Several different behaviors the wave will take:
  - Absorption, reflection, scattering, refraction, and diffraction

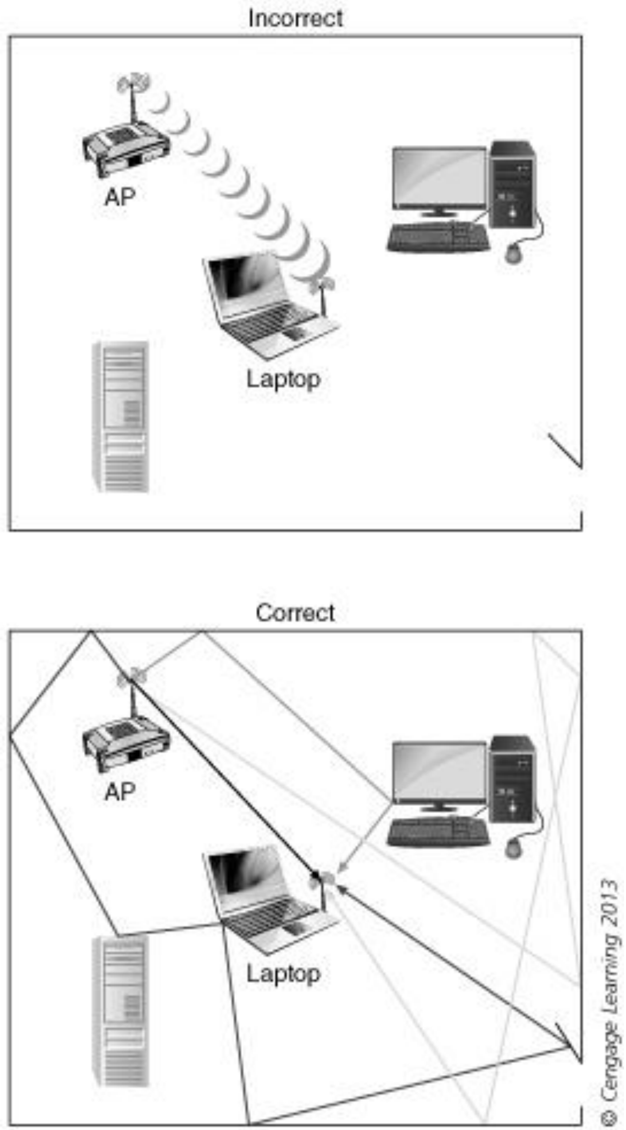


Figure 3-19 Incorrect and correct views of wave propagation and multipath

Absorption

- Materials that will “absorb” the RF signal:
  - Concrete, wood, and asphalt

Figure 3-20 Absorption

Reflection

- Reflection: when a signal is bounced back
  - Opposite of absorption
  - Caused by objects that are very large and smooth (walls, buildings, and the surface of the earth)
  - Objects made of metal will reflect a signal

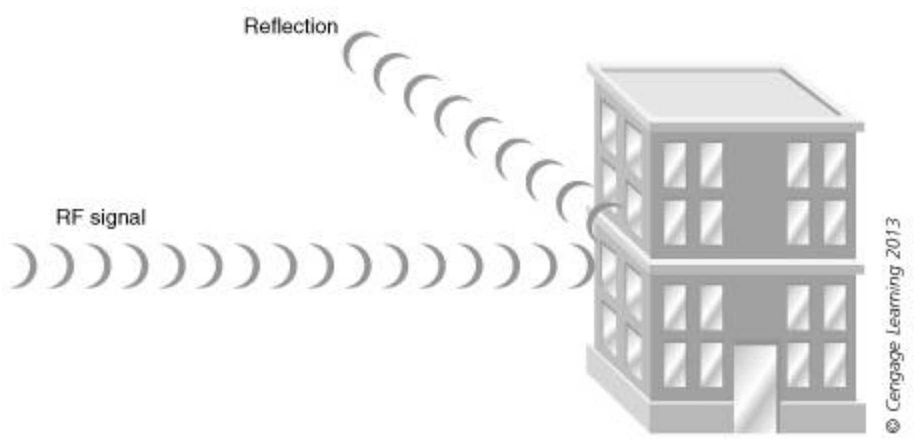


Figure 3-21 Reflection

Scattering

- Caused by small objects such as: foliage, rocks, and sand
  - Can also occur when RF signal comes in contact with airborne substances such as rain or heavy dust

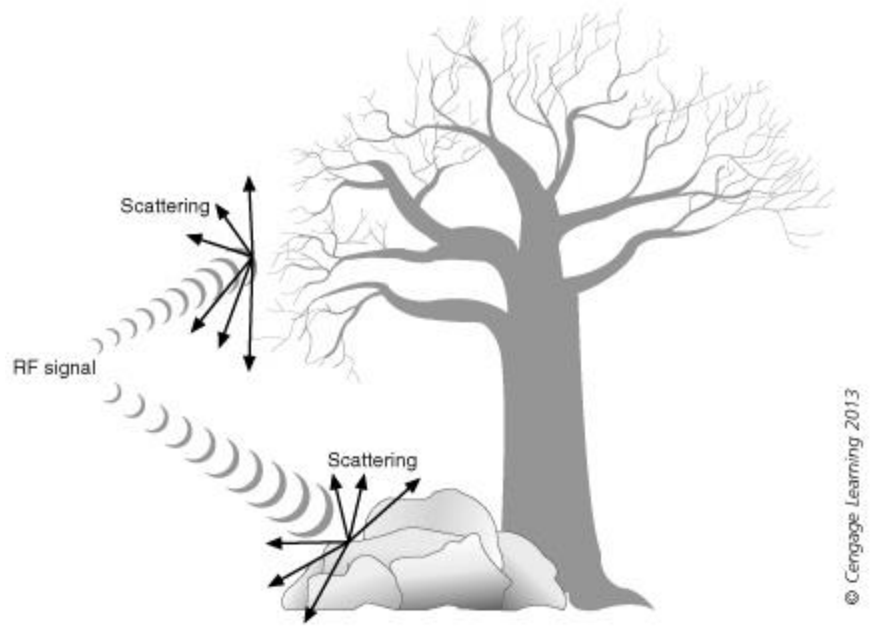


Figure 3-22 Scattering

Refraction

- When an RF signal moves from one medium to another of a different density the signal bends instead of traveling in a straight line
  - Bending behavior is known as **refraction**

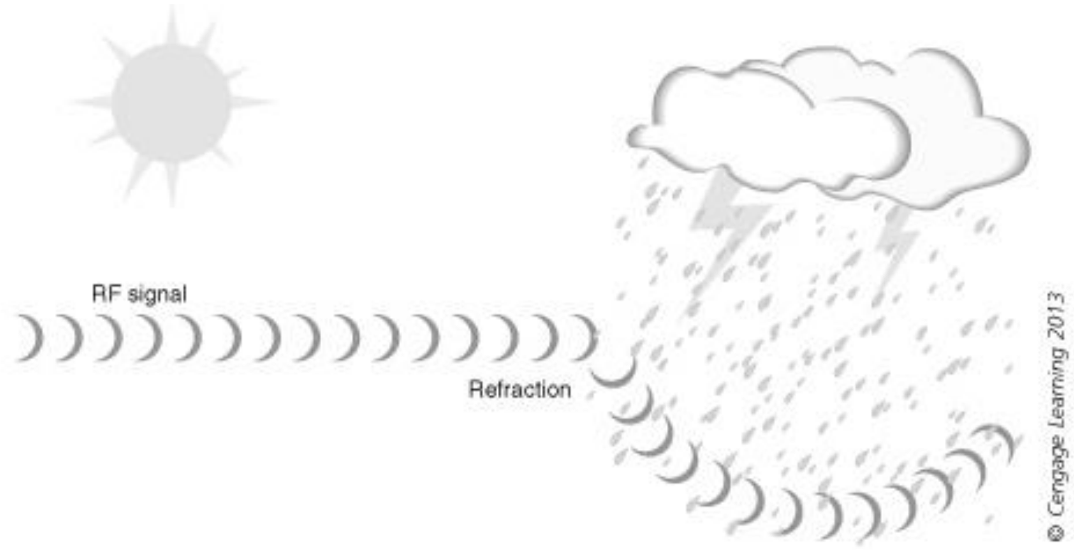


Figure 3-23 Refraction

Diffraction

- Diffraction occurs when an object with rough surfaces is in the path of the RF signal ad causes it to bend

Figure 3-24 Diffraction

Impact of Behaviors

- **Attenuation**: loss of signal strength
- Two phenomena that can result in loss of an RF signal:
  - **Free Space Path Loss (FPSL):** natural loss of signal strength through space
    - Not a result of absorption, reflection, scattering, or diffraction
  - **Delay Spread**: The difference in time of multipath signals that reach the receiver

Amplification

- **Gain:** Positive difference in amplitude between two signals
  - The strengthening of a signal
  - Achieved by **amplification** of signal

- Amplification in delay spread can occur if copies arrive at the same time as the primary signal and are in phase
  - End result is that the signal is strengthened
  - Known as **upfade**

Summary

- A form of energy known as an electromagnetic wave carries elements through the universe
- All electromagnetic waves share the same four characteristics
- Electromagnetic waves may be categorized by their frequency, wavelength, or energy needed to produce the wave
- Three types of modulations or changes to the signal can be made to enable it to carry information: amplitude, frequency, or phase

Summary

- An analog signal is a continuous signal with no breaks in it
- A digital signal consists of data that is discrete or separate, as opposed to continuous
- Almost all wireless systems use digital modulations
- Four units of measurements are used to represent RF signal strength: mW (milliwatts), dBm (decibel milliwatts), RSSI (Receive Signal Strength Indicator), and Percentage

Summary

- The behavior of the RF signal has a significant impact on the speed of the transmission and the distance between two devices
- Propagation behaviors include: Absorption, reflection, scattering, refraction, and diffraction
- Loss of signal strength is known as attenuation
- Free space path loss is the “natural” loss of signal strength through space
- The difference in time of multipath signals that reach the receiver is known as delay spread