Radio Frequency 101

An introduction to the use of RF devices

Provided by

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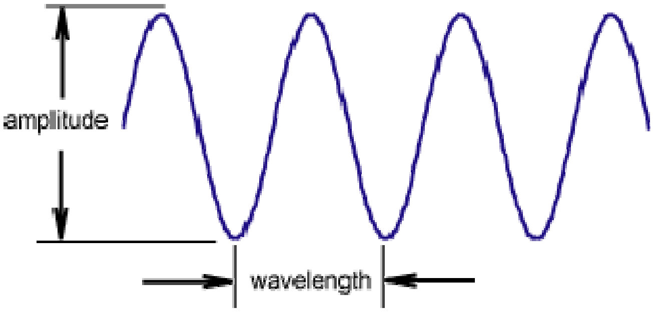
Radio Theory

Radio communications depends on two components, the transmitter (TX) and the receiver (RX). The transmitter produces or propagates electrical oscillations at a defined frequency and the receiver detects these electrical oscillations if it is tuned to the same frequency. Frequency is measured in Hertz (Hz) and is defined as the number of wavelengths (or cycles) per second (i.e., 1 Hz = 1 cycle / second). The frequency used is called the carrier wave.



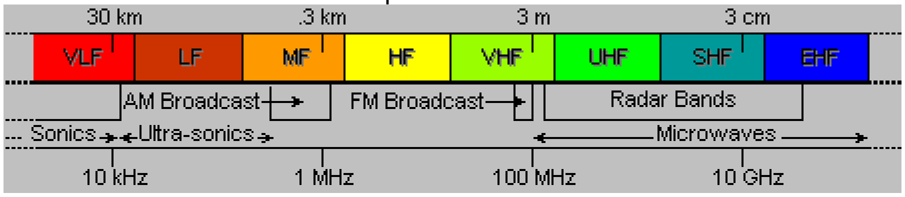
One thousand cycles per second is known as 1 kHz and pronounced one kilohertz. One million cycles per second is known as 1MHz and pronounced as one megahertz. One billion cycles per second is known as 1 GHz and pronounced as one gigahertz. The part of the electromagnetic spectrum generally thought of as radio extends from a few Kilohertz to several Gigahertz.

As the carrier frequency changes, the wavelength changes, and the resulting characteristics change. Radio waves of different frequencies are used for different purposes. Higher frequency signals have shorter wavelengths which allows more data to be conveyed in a given time period. Higher frequency signals are more easily interrupted by various objects and therefore generally cover less distance.

The frequency does not affect the speed of the signal. In a vacuum all electromagnetic waves travel at a uniform speed of about 300,000 km per second (the speed of light). In the earth's atmosphere, the physical characteristics of air can cause variations in the speed at which the radio waves travel. These variations can cause problems in communication systems. Changes in the performance of a radio-based communication system can occur due to weather. Many natural events such as storms or solar flares and man-made electrical devices can adversely affect radio frequency (RF) transmissions. Every developed country has laws designed to limit the interference caused by the various electrical devices.

The RF Spectrum

The entire range of electromagnetic frequencies that can be used for communication is referred to as the RF spectrum. This spectrum in the United States has been divided and categorized by law to provide a common agreement about the use of these frequencies.

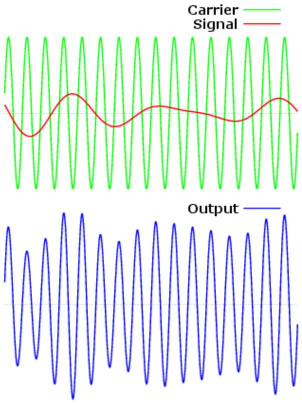


Anything below 10 kHz is considered to be audible and within the "sonic" (non RF) range.
Very Low Frequency (**VLF**) extends from 10 kHz to 30 kHz
Low Frequency (**LF**) extends from 30 KHz to 300 kHz
Mid-range Frequency (**MF**) extends from 300 kHz to 3 MHz
High Frequency (**HF**) extends from 3 MHz to 30 MHz
Very High Frequency (**VHF**) extends from 30 MHz to 328.6 MHz
Ultra High Frequency (**UHF**) extends from 328.6 MHz to 2.9 GHz
Super High Freguency (**SHF**) extends from 2.9 GHz to 30 GHz
Extremely High Frequency (**EHF**) is anything above 30 GHz
Somewhere above 100 GHz the frequencies reach the infrared and eventually visible light spectrum.

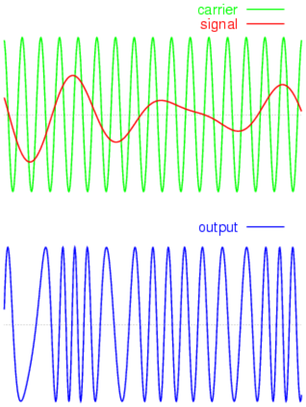
Details about the RF spectrum can be found at http://www.fcc.gov/oet/spectrum/table/Welcome.html.

Radio Communication

Data is transmitted through radio by changing or modulating the carrier frequency. When conveying an analog signal such as a voice this is commonly accomplished by either modulating the amplitude (amplitude modulation or AM) or modulating the wavelength (frequency modulation or FM). Amplitude modulation is less costly to implement but is somewhat more susceptible to atmospheric interference.

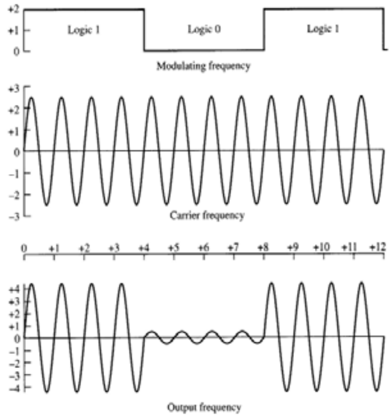


An example of amplitude modulation. The top diagram shows the modulation signal superimposed on the carrier wave. The bottom diagram shows the resulting amplitude-modulated signal. Notice how the peaks of the modulated output follow the contour of the original modulating signal. More information on AM can be found on Wikipedia at http://en.wikipedia.org/wiki/Amplitude_modulation.

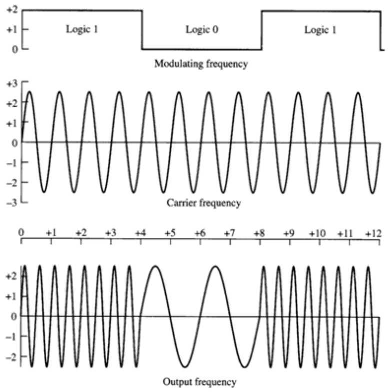


An example of frequency modulation. The top diagram shows the modulation signal superimposed on the carrier wave. The bottom diagram shows the resulting frequency-modulated signal. More information on FM can be found on Wikipedia at http://en.wikipedia.org/wiki/Frequency_modulation.

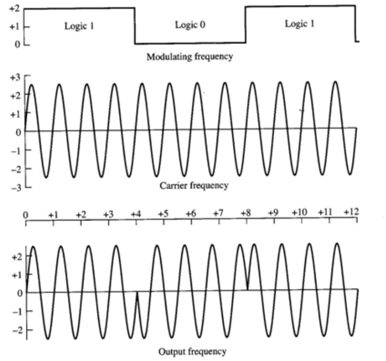
When conveying digital data, three techniques are commonly used: Amplitude-Shift Keying (ASK), Frequency-Shift Keying (FSK), and Phase-Shift Keying (PSK). A digital signal is generally conveying only one of two states (logic 1 or logic 0) rather than the range of values in an analog signal, but the techniques used are similar.



The simplest and most common form of ASK uses the presence of the carrier signal to indicate a one and the absence of the carrier signal to indicate a zero. This is also known as on/off keying. More sophisticated systems of ASK use different amplitudes to convey multiple combinations of ones and zeros to increase the bandwidth of the signal. The limit to these sophisticated systems is the signal-to-noise ratio because the closer the amplitude gets to zero the lower the power of the signal and the more likely it is that atmospheric noise can create false signals or obscure the intended signal. More information on ASK can be found at http://en.wikipedia.org/wiki/Amplitude-shift_keying.



The simplest form of FSK shifts between two frequencies close to the carrier frequency. One frequency is known as the mark-frequency and indicates a logic one. The other frequency is known as the space-frequency and indicates a logic zero. More information about FSK can be found at http://en.wikipedia.org/wiki/Frequency-shift_keying.



PSK uses a shift is the phase of the frequency being transmitted to indicate the logic one or zero. This can be implemented in several different ways including differential phase-shift keying (DPSK) and quadrature phase-shift keying (QPSK). More information about PSK can be found at http://en.wikipedia.org/wiki/Phase-shift_keying.

RF Propagation

The distance an RF signal will travel is primarily determined by the transmitter's output power and the receptivity or "gain" of the receiver and antenna. The signal is also influenced by environmental conditions and structures. While the available power is the chief factor in the range of a signal, the efficiency with which the power is employed also affects the range.

The design of the transmitter's antenna determines the shape of the electromagnetic field (radio wave) delivered or propagated. The field delivered from an antenna extends into the space surrounding it and its strength diminishes as the distance increases. When there are no obstructions, the signal decreases directly according to the square of the distance from the antenna. In other words a signal measured at four meters from the antenna will have twice the strength as a signal measured at sixteen meters from the antenna.

Obstructions (such as the earth itself) or atmospheric absorption may further reduce the strength of the signal. Anything that contains liquid such as vegetation, people, and bodies of water tend to absorb RF signals. The effective range is also affected by the angle or polarization between the transmitter's antenna and the receiver's antenna.

Just as ripples in a pool reflect off the side of the pool, so too radio waves will reflect off surfaces. The nature of the reflection depends on the frequency of the radio wave and the composition of the surface it encounters. When radio waves reflect they create multiple signals which can cause interference. When a radio wave is reflected the reflected component may reach the receiver at a different time than the original wave traveling in a straight line. The receiver must be able to recognize these as the same signal or discard the unnecessary components.

When multiple waves cross paths, the wave patterns may cancel or reinforce each other. This can be seen as a false signal or eliminating parts of the signal altogether. This phenomenon is known as multi-path attenuation.

Every environment contains some ambient RF noise. Generally it is caused by natural source or other equipment. The receiver distinguishes the signal from the ambient noise. This only works as long as the signal is sufficiently stronger than the noise. Equipment that contributes to ambient noise includes electric motors, fluorescent ballasts, high-power electrical switching equipment and any radio transmitting equipment. Radio transmitters can cause problems even if they are not transmitting on the same frequency due to harmonics.

No RF transmission is propagated only at the frequency intended. Transmission is at its strongest at the intended frequency and then trails off only to peak again to a lesser degree at a frequency that is some multiple of the original frequency. We call these lesser peaks harmonics of the original frequency. For example 433 MHz has its first harmonic at 866 MHz (2 * 433 = 866). Well designed transmitters minimize harmonics as much as possible, but because we live in the real-world harmonics will exist.

To summarize, the signal of any RF system is affected by:

- Transmission power
- Receiver gain
- The antenna type and placement
- Environmental obstructions
- Environmental surfaces
- Other sources of RF energy

Generally speaking the transmission power and receiver gain are determined by the design of the product being used, but if the device is battery powered good battery maintenance is important to make sure the device is always operating at its optimal power.

Antenna

An antenna is essentially a transducer that converts electrical currents into electromagnetic waves or vice versa. Put another way an antenna is anything that converts a signal from the circuit board to the airwaves and back again. Antennas (or antennae if you are a stickler for correct English) can be intentional devices produced for that purpose or unintentional components of a system accidentally receiving or transmitting spurious signals.

In the United States the Federal Communications Commission (FCC) requires that all electrical devices sold comply with the FCC's standard Part 15 which states that electrical devices may not interfere with the proper operation of other devices and must be able to operate properly with some level of interference from other electrical devices. Therefore electrical devices are generally designed to minimize unintentional antennas, but when installing RF-based equipment it pays to stay alert for possible sources of interference.

The intentional antenna can be anything from a simple wire to a tuned Yagi antenna. There are many styles of antennas and the selection of the proper antenna can be a very sophisticated exercise in engineering. For the purposes of this introductory lesson, we will limit the discussion to some basic characteristics of antennas.

The characteristics of an antenna used for the receiver and the transmitter are generally similar. In many cases it makes sense to use identical antennas, but in some applications it may make sense to use different antennas for the receiver and transmitter or even different antennas for different placements of the receivers or transmitters.

Since the electromagnetic wave exists in space, it has dimensions that are important to understanding how it behaves. The critical dimension is known as the wavelength. The wavelength, as shown earlier, is the distance the radio wave travels during one complete cycle of the wave. This length is inversely proportional to the frequency and may be calculated according to the following formula:

$$\text{Wavelength (inches)} = 11{,}811 / \text{frequency (MHz)}$$

The length of a monopole antenna is measured in relationship to the ground plane. The ground plane is a solid conductive area used in the design of the circuit board. The ground-plane provides an electrical reference point in the design.

Generally the gain of an antenna is measured in decibels (dB). dB is the ratio between two power levels, expressed as a logarithm, and is used to describe the effect of the antenna on signal strength. Since the dB scale is a logarithmic measure, it represents large-scale variations in signals in smaller numbers. It is very useful because system gains and losses can be calculated by adding and subtracting numbers.

Every time you double (or halve) the power level, you add (or subtract) 3 dB to the power level. This factor of two corresponds to a 50% reduction or a 100% gain. 10 dB gain/loss corresponds to a ten-fold increase/decrease in signal level. A 20 dB gain/loss corresponds to a hundred-fold increase/decrease in signal level. In other words, a device (like an antenna) that has 20 dB loss will only be transmitting 1% of its potential signal. Thus, big variations in signal levels are easily handled with smaller numbers.

Transmitter

The transmitter's antenna allows RF energy to be radiated from the output stage of the electronics into free space. In many transmitter designs the transmitter's output power is often set higher and the legal objectives are achieved with the selection of a less efficient antenna to meet size, cost, or cosmetic objectives. Since gain is easily improved at the transmitter, its antenna can generally be less efficient than the antenna used at the receiver.

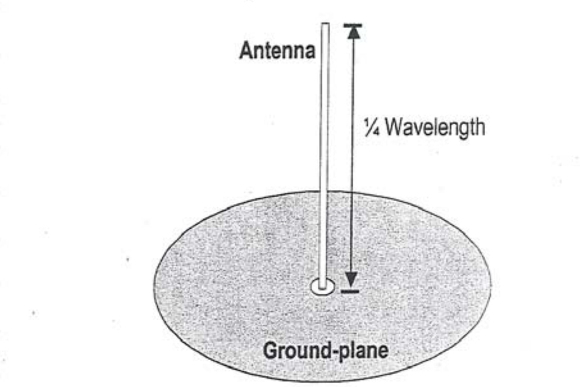
Receiver

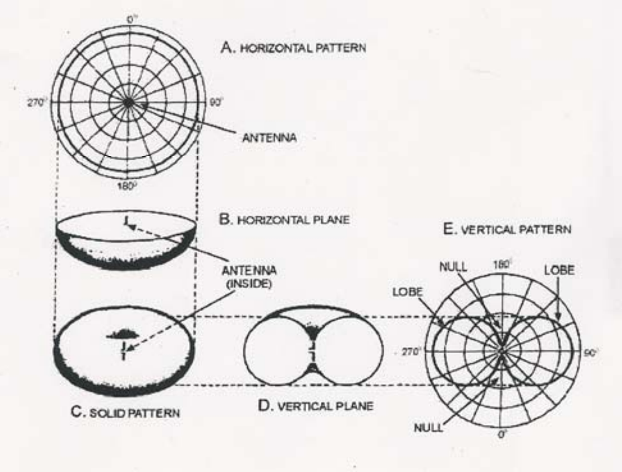
The receiving antenna intercepts the electromagnetic waves radiated from the transmitting antenna. When the receiving antenna intercepts these waves, they induce a small voltage. This voltage causes a weak current to flow, which contains the same frequency as the original current in the transmitting antenna.

A receiving antenna should capture as much of the intended signal as possible and as little as possible of other different frequency signals. It should give its maximum performance at the specific frequency used by the transmitter or in the same band for which the receiver was designed. The efficiency of the receiver's antenna is critical to maximizing the possible range. Unlike the transmitter antenna, where legal operation may mandate a reduction in antenna efficiency, the receiver's antenna should be optimized as much as practical.

Whip Antenna

The simplest antenna is the "whip" antenna. This typically is a straight conductor with a length from the ground-plane that is equal to ¼ of the wavelength of the signal being sent. The whip antenna is connected to one side of the transceiver and the ground-plane is connected to the other side of the transceiver. The circuit is then completed through the electromagnetic field between the antenna and the ground-plane. Ideally the ground plane should spread out at least one quarter wavelength or more around the base of the whip. The ground-plane can be smaller, although it will affect the performance of the whip.





With this configuration, the best results are obtained around the antenna in a horizontal plane with both the transmitting and receiving antenna having the same polarization or spatial orientation. When directional antennas are used the polarization or orientation of the antenna becomes even more important.

dBd (dB dipole) The gain an antenna has relative to a dipole antenna at the same frequency. A dipole antenna is a standard low-gain, low-cost antenna. The reason why the gain of many antennas, especially VHF/UHF antennas, is measured in dBd is because antenna manufacturers calibrate their equipment using a simple dipole antenna as the standard. Then they replace it with the antenna they are testing. The difference in gain (in dB) is referenced to the signal from the dipole.

dBi (dB isotropic)

The gain a given antenna has relative to theoretical isotropic (point source) antenna. Unfortunately, an isotropic antenna cannot be made in the real world, but it is useful for calculating theoretical fade and System Operating Margins. The gain of Microwave antennas (above 1 GHz) is generally given in dBi. A dipole antenna has 2.14 dB gain over a 0 dBi isotropic antenna. So if an antenna gain is given in dBd, not dBi, add 2.14 to it to get the dBi rating, For example, it an omni antenna has 5 dBd gain, it would have 5 + 2.14 = 7.15 dBi gain.

EIRP (Effective Isotropic Radiated Power)

Effective Isotropic Radiated Power is defined as the effective power found in the main lobe of a transmitter antenna relative to an Isotropic radiator which has 0 dB of gain. It is equal to the sum of the antenna gain (in dBi) plus the power (in dBm) into that antenna. For example, if a 12 dBi gain antenna is fed with 15 dBm of power has an Effective Radiated Power (ERP or EIRP) of:

12 dBi + 15dBm = 27 dBm (500 mW).

FSL (Free Space Loss)

Free Space Loss is defined as the loss that a radio signal experiences when traveling through free space. The formula to calculate FSL is:

FSL(dB) = 20 * Log_{10} (frequency in MHz) + 20 * Log_{10} (Distance in Miles) + 36.6

Example: At 5 miles FSL is 118 dB

NOTE: Every time you double (or halve) the distance from the transmitter to the receiver, the signal level is lowered (or increased) by 12dB.

System Operating Margin (SOM)

System Operating Margin (also referred to as Fade Margin) is defined as the difference between the received signal level (in dBm) and the receiver sensitivity (in dBm) needed for error free reception. The received signal level is calculated by:

Rx Signal Level (dB) = Tx Power – Tx Cable Loss + Tx Antenna Gain – FSL + Rx Antenna Gain – Rx Cable Loss

SOM = Rx Signal Level – Rx Sensitivity

10 dB of SOM should work if there is not bad interference. We recommend 10 dB SOM or more. 20 dB is excellent.