CODAN
COMMUNICATIONS

Radio System Basics and RF Fundamentals

TRAINING GUIDE

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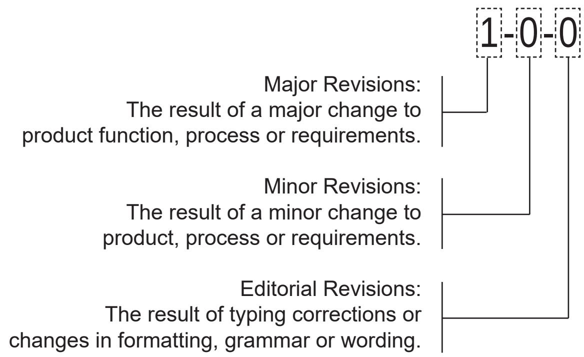
Radio System Basics and RF Fundamentals

Training Guide

NOTE

DOCUMENT REVISION DEFINITION

Documentation uses a three-level revision system. Each element of the revision number signifies the scope of change as described in the diagram below.



Three-level revision numbers start at 1-0-0 for the first release. The appropriate element of the revision number is incremented by 1 for each subsequent revision, causing any digits to the right to be reset to 0.

For example:
If the current revision = 2-1-1 Then the next major revision = 3-0-0
If the current revision = 4-3-1 Then the next minor revision = 4-4-0
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DANIELS ELECTRONICS IS NOW CODAN COMMUNICATIONS

On August 7th, 2012 - Codan Limited (ASX: “CDA”) announced the acquisition of Daniels Electronics Limited, a leading designer, manufacturer and supplier of land mobile radio communications (LMR) solutions in North America. The acquisition of Daniels delivers on Codan’s stated strategy of growing market share and diversifying its radio communications product offering. Codan Limited designs, manufactures and markets a diversified range of high value added electronic products, with three key business divisions; radio communications, metal detection and mining technology.

ABOUT CODAN COMMUNICATIONS

Codan Communications is a leading international designer and manufacturer of premium communications equipment for High Frequency (HF) and Land Mobile Radio (LMR) applications. We’ve built our reputation for reliability and customer satisfaction over 50 years in radio communications, in some of the toughest conditions on the planet.

For over 50 years Codan has provided customers in North America and internationally with highly reliable Base Stations and Repeaters that are environmentally robust to operate in rugged and extreme temperature conditions where low current consumption (solar powered) is a key requirement.Codan is a pioneering member of the P25 Digital standard, for radio system interoperability between emergency response governmental organizations, providing enhanced functionality and encryption. Our products operate between 29 - 960 MHz and are available in a variety of Base Station and Repeater configurations for two way voice and mobile data applications.

Our self-servicing customers range from Forestry and National Park services through Police and Fire departments and on to Utility and Transportation groups. Our products have been deployed in every imaginable situation from the Antarctic to Hawaiian mountaintops to Alaska, enabling respondents to Forest Fires, Ground Zero rescue and routine patrols. Codan is an industry leader in Analog and P25 radio systems design. We offer modular rack-mounted Base Stations and Repeaters capable of operating in VHF, UHF, 700 MHz, 800 MHz, and 900 MHz

ABOUT THE AUTHORS

Przemek Mroz is a professional engineer registered with the Professional Engineers and Geoscientists of British Columbia (P.Eng) , has a Bachelor’s Degree in Electrical Engineering from the University of Victoria (B.Eng), and a Diploma in Electronics Engineering Technology from the Southern Alberta Institute of Technology. Przemek has been with Daniels / Codan since 2003, and has worked in a variety of roles including manufacturing, engineering and sales.

Pete Lunness is a member of the Applied Science Technologists & Technicians of British Columbia, has a Diploma in Electronics Engineering Technology from Camosun College and a Certificate in Adult and Continuing Education from the University of Victoria. Pete has been at Daniels / Codan since 1996, working in engineering, sales and customer support, and has been instructing technical training courses since 1998.

RESOURCES

Codan Communications provides many resources for the testing, tuning, maintenance and design of your Codan MT-4E Analog and P25 Digital Radio System.

Instruction Manuals

Codan instruction manuals are very comprehensive and include information on:

Theory of operation
Detailed Specifications
Testing and tuning instructions
Component layout illustrations

Instruction manuals can be obtained from the factory.

Technical Notes

Technical notes outline key aspects of tuning, installing, maintaining and servicing Codan Radio Systems.

Technical Notes can be found online at www.codancomms.com.

Application Notes

Application Notes provide an overview of the range of applications in which Codan Radio systems can be used.

Application Notes can be found online at www.codancomms.com.

P25 Training Guide

The P25 Training Guide provides the reader with a simple, concise and informative description of Project 25.

The P25 Training Guide can be found online at www.codancomms.com.

MT-4E Analog and P25 Digital Radio Systems User Guide

The MT-4E User Guide provides an overview of the configuration, operation and programming of Codan MT-4E radios.

The MT-4E User Guide can be found online at www.codancomms.com.

MT-4E Analog and P25 Digital Radio Systems Maintenance Guide

The MT-4E Maintenance Guide is an aid to configuring and testing Codan MT-4E radios using an IFR 2975 Service Monitor by Aeroflex. The Guide is intended to be used with IFR 2975 Setup files that can be loaded into the Service Monitor.

The MT-4E Maintenance Guide can be found online at www.codancomms.com

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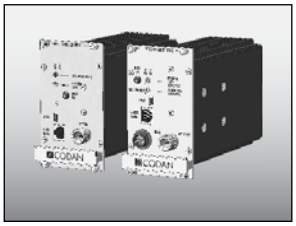


CHAPTER 1: INTRODUCTION

This guide covers many of the basic concepts that apply to the multitude of ways radio communications are used every day.

SCOPE AND RECOMMENDED ORDER OF READING

Although anyone interested in how radio works can benefit from the contents of this text, it is important to note that it is written with the beginner Land Mobile Radio (LMR) user in mind and therefore is focused on these technologies.

The information in this text is laid out in a progressive manner; it is therefore recommended that the reader follow the sections in order (rather than jumping to various sections), so that no important concepts are missed.

PRE-REQUISITE TECHNICAL KNOWLEDGE

The aim of this text is to provide the reader with a solid understanding of how a radio system works without delving too far into technical, mathematical and engineering detail; however, some fundamental concepts must be in place for the information presented to be understood.

In this short introductory section, we will take a brief look at some of these concepts as either an introduction or review, depending on the reader's experience.

Land Mobile Radio

Land Mobile Radio (LMR) is a form of wireless electronic communication in which land-based users use terrestrial radio infrastructure to communicate with other users.

The user's point of interface into an LMR system is most often a handheld "walkie-talkie" device, a vehicle–mounted transceiver, or a dispatch console.

The applications most often associated with LMR are law enforcement, remote land management, emergency services, the military and various commercial and industrial applications.

Electricity and Magnetism

Radio communications are made possible in human understanding of naturally-occurring electric phenomenon. All matter is composed of tiny atoms, which in turn are made of even smaller charged particles; the number and configuration of these particles is what gives matter its characteristics. In the natural state, atoms always have a set number of charged particles, but when forced, can shed or acquire negatively charged particles called electrons.

In the situation when one atom that has acquired an extra electron is in close enough proximity to another atom that is lacking an electron, the extra electron will "jump" the space between the atoms (see Figure 1-1). The natural tendency to return to equilibrium and the energy expelled in doing so is the basis of electricity.

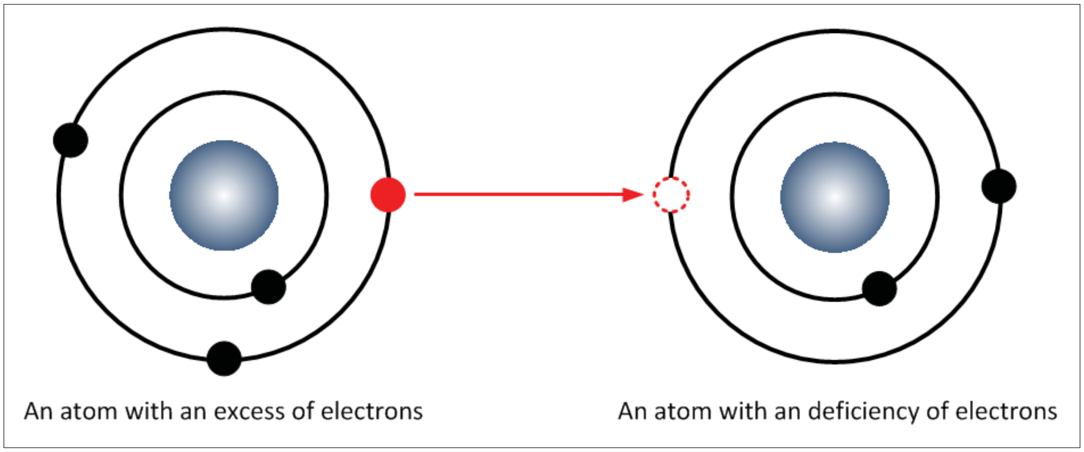


Figure 1-1: Electron Movement

Now picture this action on a larger scale: in one area there is a material made of a huge number of atoms in which there is a lack of electrons. In another area there is a material made of a huge number of atoms in which there is an excess of electrons. In this physically separated state there exists an amount of electric potential energy, known as potential difference, or voltage, since the excess electrons naturally want to fill the spaces where there is a lack of electrons. Voltage is measured in the numerical unit **Volts** (represented by the symbol ‘V’).

Electrical Circuit

If one were to place a material that allows electrons to move easily (called a conductor) between the two areas, the potential energy is converted to kinetic energy as the electrons travel from one area to the other (see Figure 1-2). This flow of electrons along the conductor is known as electronic current, the rate-magnitude of which is measured in **Amperes** (represented by the symbol ‘A’).

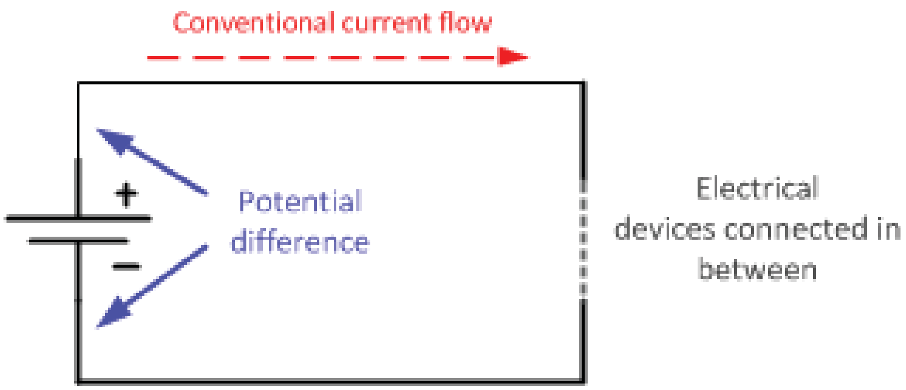


Figure 1-2: Electrical Circuit

The area of excess electrons (known as the negative since it has an excess of negative charges), the area of lacking electrons (known as the positive, since the lack of negative charges makes it positively charged) and the conductor make an entirety called a **circuit**.

One can control the flow of electrons through a conductor by adding resistance to the conductor; this still allows electrons to flow, but not as freely as in a simple conductor. As a result, potential energy is created between the beginning point of the resistance and the end. Resistance is measured in the numerical units **Ohms** (represented by the Greek symbol ‘Ω’).

The relationship of resistance, current and voltage is expressed by a mathematical equation known as Ohm’s Law:

$$V = I * R$$

Depending on how the electricity is generated, the current can flow steadily in one direction, known as Direct Current (DC), or it can cyclically change direction at various rates, which is known Alternating Current (AC).

When electricity is applied to an object, it is used to produce work on that object by transferring electrical energy into another form of energy; for example, when electricity is connected to a lightbulb, it is used to produce work in the form of light and heat.

The amount of work performed (or more specifically the rate at which the work is performed), is known as the electrical power and is measured in **Watts** (represented by the symbol ‘W’); power is therefore often used as a practical measure of how much of something (for example, heat, light, radiation) is produced by an electric / electronic device. The relationship of power to voltage, resistance, and current are shown by the mathematical equations below:

$$P = E * I = I^2 * R$$

Magnetism

Magnetism is a natural force of nature that causes attraction or repulsion of like materials that produce magnetic fields. Magnetism extends from an object in an invisible field that decreases in strength the further you move away from an object.

Magnetism and electricity are closely related; when electricity moves through an electrical conductor, a magnetic field is created around the conductor. Conversely, when a conductive material is moved through a magnetic field, an electrical current is generated within the conductor.

Basic Electronic Elements

While this text does not explore radio communication electronics on a circuit level, it is useful to know the basic electrical elements that comprise electronic circuits:

- ***Resistor***: an element made of a material that resists, but does not stop the flow of electrons in an electrical circuit (i.e., adds resistance). A resistor is rated by the unit of resistance; the **ohm** (Ω) and retains the same resistance properties in both AC and DC applications. See Figure 1-3.

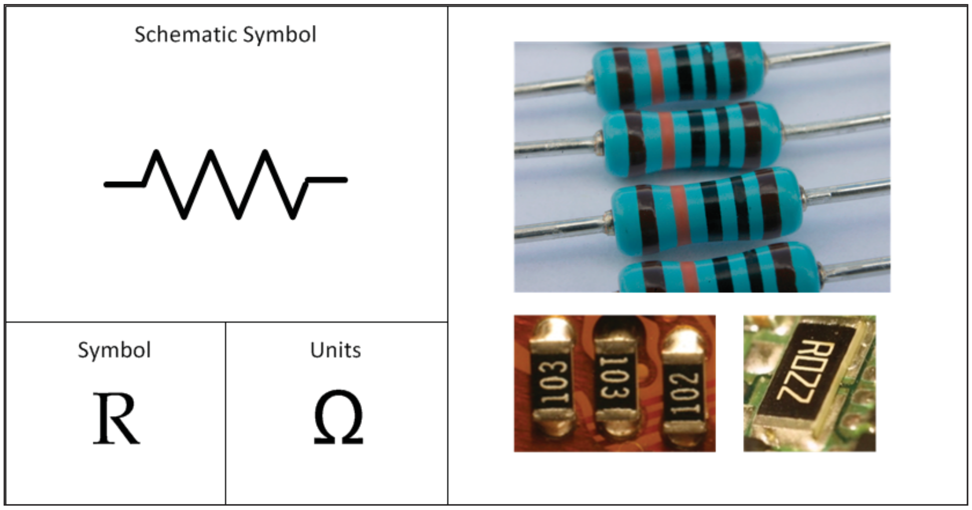


Figure 1-3: Resistors

- ***Capacitor***: an element made from two conducting plates separated by a non-conducting material (called a dielectric) that has the ability to store and discharge electric energy. A capacitor is rated by the unit of capacitance; the **Farad** ('F'). See Figure 1-4.

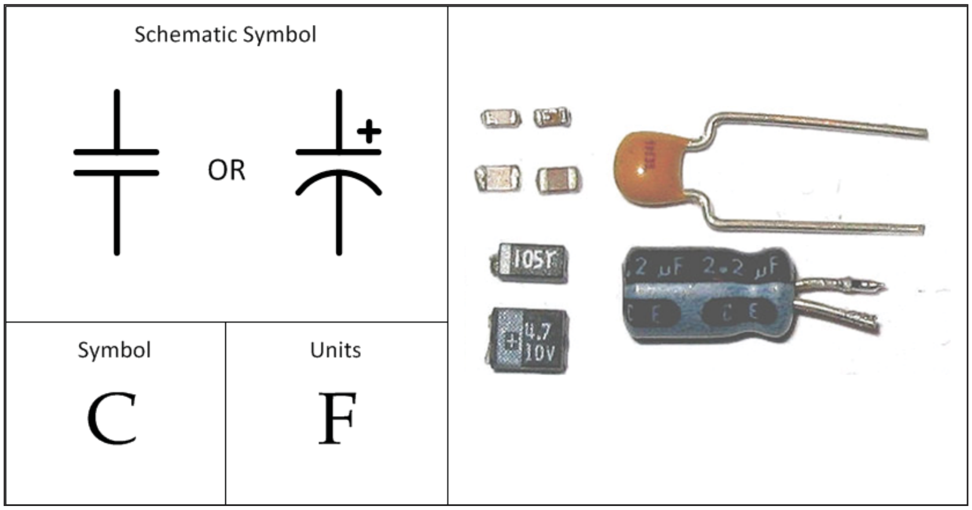


Figure 1-4: Capacitors

In a DC application, a capacitor has an infinite resistance, since the two plates of which it comprises never touch and therefore do not complete a circuit. In an AC application, the resistive properties decrease as the frequency of the AC voltage increases due to a field of electric potential being generated between the plates.

- ***Inductor***: an element made of a conductive wire (typically copper) wound into a coil that resists changes in current flow (not to be mistaken with resistors that resist the current itself). An inductor is rated by the unit of inductance; the **Henry** ('H'). See Figure 1-5.

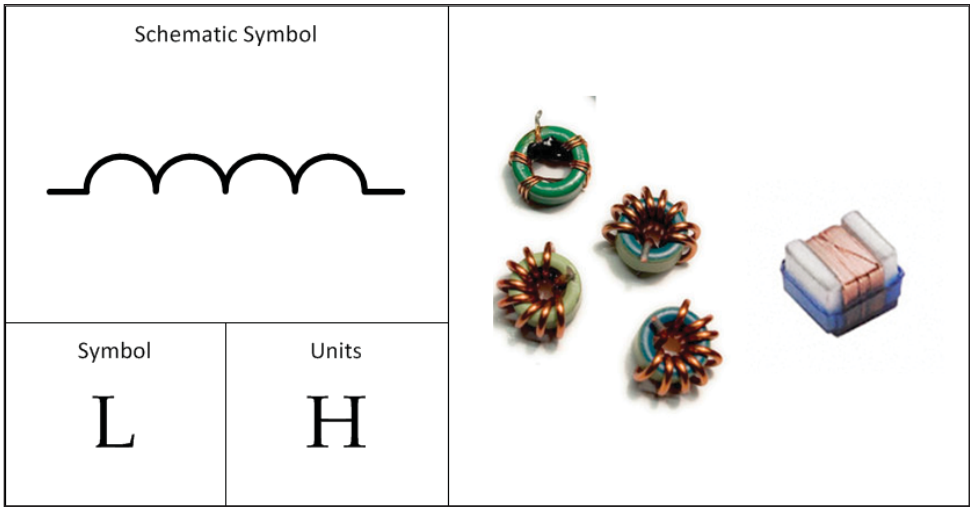


Figure 1-5: Inductors

In a DC application, an inductor has no resistance, since it is made of a conductive wire. In an AC application, its resistive properties increase as the frequency of the AC voltage increases due to the magnetic fields generated within the wire.

- ***Semiconductors***: a category of electronic components (rather than a single element as shown in previous examples), that allows for variable flow of current depending on arrangement and application; for example, a semiconductor device called a **diode** allows for current to flow in one direction, but not in another. Another example is a **transistor**, which allows the current flowing through it to be varied by external control voltage (or current).

Capacitors and inductors are particularly important in radio communications electronics; their variable properties when AC electricity is applied are exploited greatly in making radio communications work. Semiconductors and resistors are ubiquitous throughout all electronics and are also indispensable when dealing with radio communication technology.

MATHEMATICAL REPRESENTATIONS

Mathematics is the language that technologists and engineers use to express and understand the physical and technical phenomenon involved in radio communications. While the mathematics beyond simple algebraic equations (for example a value x equals a particular number) are all but omitted from this text, it is unavoidable that some things must be represented using the standard mathematical representations used in the radio communications industry.

Graphs

A graph (or chart) is a graphical representation of the mathematical relationship between two separate types of numerical data.

A simple graph consists of two axes: a horizontal x-axis and a vertical y-axis. Each axis is assigned a type of numerical data (which may be positive or negative in value). The body of the graph is filled with individual points, curves or lines representing the relationship between the numbers on the x-axis and the numbers on the y-axis (see Figure 1-6).

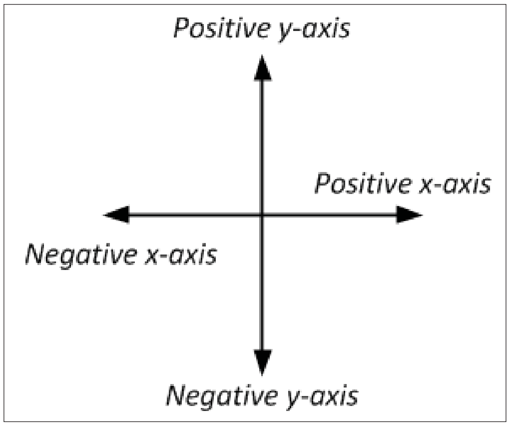


Figure 1-6: Simple Graph Axes

The graphs that will be used in this text will typically have one of the two configurations:

1. Amplitude (of Voltage, for example) on the y-axis **versus time** on the x-axis, thus representing how the amplitude changes over time (see Figure 1-7).

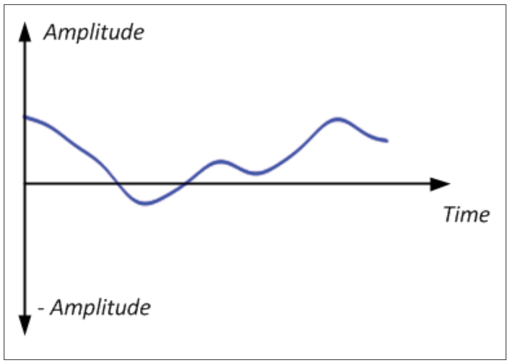


Figure 1-7: Time Graph

2. Amplitude (of Voltage, for example) on the y-axis **versus frequency** on the x-axis, thus representing what amplitude is present at a given frequency (see Figure 1-8).

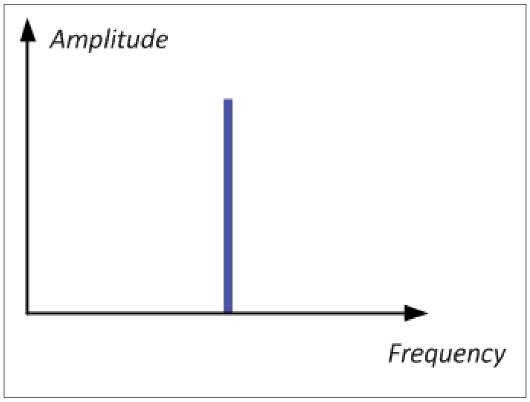


Figure 1-8: Frequency Graph

Mathematical Notation

The numbers used to represent values in radio communication can range from the very small to the very large and are therefore not conveniently expressed using standard numerical terms.

To solve this problem, powers of ten and metric prefixes are often used.

Powers of Ten

When writing very large or very small numbers, it is most often convenient to not have to write a lot of zeros or to "round off" digits that are insignificant. To do this, one can take advantage of the fact that multiplying or dividing by 10 moves the decimal point in a number; thus one can express a number as a small, single digit number multiplied a number of times by ten.
For example:
1,100.0 can be written as 1.1 x 10 x 10 x 10, since this multiplication will result in the original number.

To simplify further, we use powers to avoid writing multiplications of ten, over and over; in the example we multiply by ten three times, therefore we write 10^3. Summarizing this example:

$$\mathbf{1{,}100.0 = 1.1 \times 10 \times 10 \times 10 = 1.1 \times 10^3 = 1{,}100.0}$$

Metric Prefixes

For more commonly used magnitudes of numbers, i.e., those within the range of $10^{\pm 12}$, convenient metric prefixes are used to ease expression further when stating numbers that have associated units (i.e., measurements). A metric prefix is a standard "word" and associated symbol that is attached to the unit of a measurement, after the number itself, to indicate multiplication by multiples or fractions (i.e., division) of factors of ten. Adding a metric prefix allows one to state very large or very small numbers more easily by moving the decimal point of the number and using the analogous prefix word to express its size.

For example, if an element in a circuit has a resistance value of 1100.0 Ω (or "one-thousand, one hundred ohms"), it is simpler to move the decimal point to the left by three spaces and express the number as 1.1 kΩ (or "one-point-one kilo-ohms).

The table below (see Table 1) shows the most commonly used metric prefixes in radio communications.

Table 1: Common Metric Prefixes

Metric Prefix	Symbol	Multiplier	Power of Ten
Tera	T	1,000,000,000,000	10^{12}
Giga	G	1,000,000,000	10^{9}
Mega	M	1,000,000	10^{6}
kilo	k	1,000	10^{3}
mili	m	0.001	10^{-3}
micro	µ*	0.000 001	10^{-6}
nano	n	0.000 000 001	10^{-9}
pico	p	0.000 000 000 001	10^{-12}

**** The Greek letter mu***

Decibels

The unit of decibels is a convenient way of expressing the ratio or relative quantity of two numbers.

The symbol for **decibels** is dB. Decibel expressions are most often used in radio communications to show a relative increase or decrease in electrical power; typically, the expression is relative to 1W or 1 mW (in which case the symbol is changed to dBm).

The mathematical expression to represent in decibels a given power in watts (P) relative to a reference power in watts (P_0), is shown below:

$$10 \log_{10}\left(\frac{P}{P_0}\right) \text{dB}$$

Using decibels is convenient because it allows large figures and fractions to be represented by smaller whole numbers and because it allows multiple changes in a quantity (like electrical power) to be more easily calculated using simple addition and subtraction of dB units. The table below (see Table 2) shows some examples of this expression in practice.

Table 2: Mathematical Expressions for Decibels

Decibels (dB)	Power Ratio (P/P_0)	Notes
20	100	P is 100x greater than P_0
10	10	P is 10x greater than P_0
3	1.995 (approx. 2)	P is approx. 2x greater than P_0
0	1	P is the same as P_0
-3	0.501 (approx. ½)	P is approx. half of P_0
-10	0.1	P is 10x smaller than P_0
-20	0.01	P is 100x smaller than P_0
-60	0.000001	P is one million times smaller than P_0

A Note About Radio Terminology

The terminology used in electronic communications is often subject to variation due to manufacturer preference, individual preference and use in other similar technologies and applications.

Readers who have a background in this field or another related field will note that this text may either call something they are familiar with by a different name, or use a familiar term to describe a different concept; unfortunately, this often results in confusion.

Listed below are some examples to watch out for in later sections of this guide:

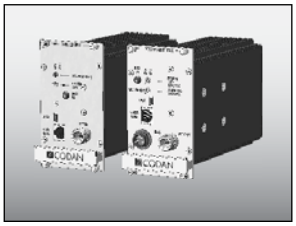
- *Manufacturer specific terms*: The proprietary term ‘PL tone’ is often used instead of the industry standard term ‘CTCSS tone’.
- *Individual preference*: To some users, a trunk is an RF link between two sites; to others, trunking is a form of radio communications using computer control of frequency / channel selection.
- *Variation across similar technologies*: The terms ‘Simplex’ and ‘Duplex’ have a different meaning to IT professionals.

While this guide is written to capture as much of this variation as possible, the first term presented will always be the industry standard term.

Introduction to Regulatory Bodies

Much of the information presented in this guide is determined by following radio communication industry standard principles, values and techniques. These are defined by a large number of organizations tasked with licensing, standardizing and providing information to the public. Some of these organizations are listed below:

- The **Federal Communications Commission (FCC)** is an independent United States government agency, charged with regulating interstate and international communications by radio, television, wire, satellite and cable. The FCC regulates the use of radio spectrum to fulfill the communications needs of businesses, local and state governments, public safety service providers, aircraft and ship operators, and individuals.
- The **National Telecommunications Information Administration (NTIA)** is the U.S. government’s telecommunications policy office. The NTIA assigns and administers frequencies to federal agencies.
- **Industry Canada (IC)** is the lead department for radio, spectrum and telecommunications issues in Canada.
- The **International Telecommunication Union (ITU)** is a treaty organization affiliated with the United Nations. Its charter includes the regulation and use of the radio spectrum worldwide.
- The **Telecommunications Industry Association (TIA)** represents manufacturers of telecommunications equipment and prepares standards for the telecommunications industry. TIA represents the communications sector of the Electronic Industries Alliance (EIA).
- The **Association of Public-Safety Communications Officials International (APCO)** provides leadership; influences public safety communications decisions of government and industry; promotes professional development; and fosters the development and use of technology for the benefit of the public.



CHAPTER 2: BASIC RADIO ELEMENTS

THE CONCEPT OF RADIO COMMUNICATIONS

Radio communication is defined as the transmission, reception and processing of information over the air between two locations by using electronic equipment that sends and receives electromagnetic signals.

The reason that we use radio communications is that, as human beings, our physical senses limit the distance over which we can receive information from others; we are at the mercy of our eyes and ears. Radio communications were invented as a means of overcoming these limitations by allowing people to communicate over vast distances at great speeds by the use of electronic devices.

THE NATURE OF ELECTROMAGNETIC SIGNALS

Electromagnetic Energy

The electronic devices used in radio communication create electromagnetic energy that is “imprinted” with information that can be perceived and interpreted by humans, such as sound.

Electromagnetic energy is a type of energy that occurs with when particles of matter interact on an atomic level. It has a component of electric potential and a corresponding magnetic component, because the movement of electrons (i.e., electricity) creates magnetism. The opposite is also true. If one moves a magnet around an electrical conductor, an electric current is generated (see Figure 2-1).

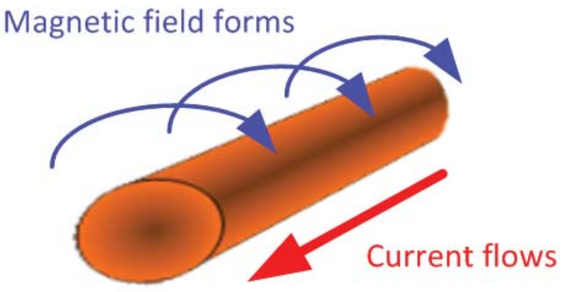


Figure 2-1: Magnetism and Current

Electromagnetic energy is mostly invisible (the exception being light, which is a form of electromagnetic energy our eyes are capable of sensing), travels through the air, and sometimes, through solid matter. It is all around us at all times and in varying forms, both naturally and artificially created.

The electromagnetic energy used in radio communications is created by cyclically varying electric potential (voltage) in a transmission medium, such as a wire or the air (in the case of radio). The result is a time-varying field of electric potential and magnetic force known as an **Electromagnetic (EM) Field** that radiates out from its source in a repeating, wave like manner; hence the often used term ‘radio waves’.

The magnetic and electronic components vary in proportion to each other and both are perpendicular to each other; the magnitudes of both are perpendicular to the direction in which the wave travels. This is most easily shown in the diagram below (see Figure 2-2):

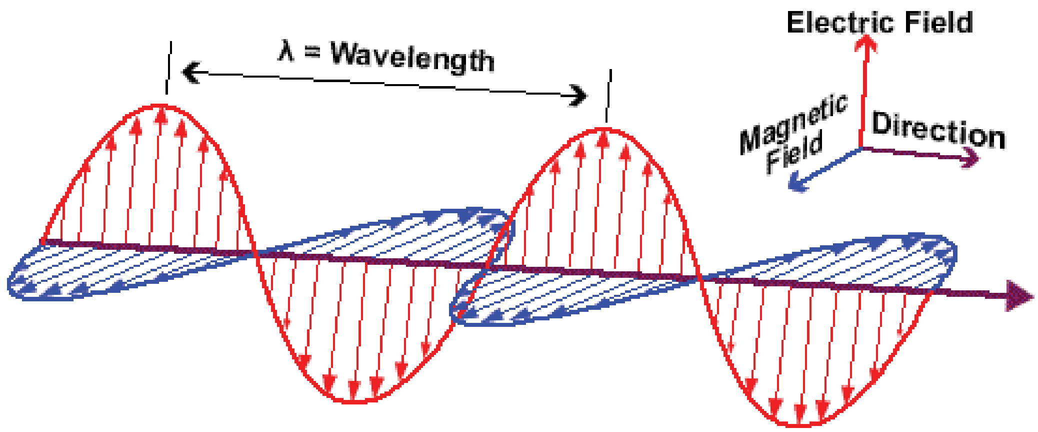


Figure 2-2: Illustration of an Electromagnetic Field

Amplitude, Frequency and Power

The wave-like change of electromagnetic energy over time is represented by a sinusoidal (sine) wave. This has four key attributes that define the nature and behavior of a radio wave:

1. Amplitude
2. Frequency
3. Phase
4. Wavelength

***Amplitude* (A):** The electric potential intensity of the wave (see Figure 2-3). There are several ways that amplitude can be expressed:

- *Instantaneous voltage* (v): The voltage value at any given instant of time.
- *Peak voltage* (Vp): The maximum value that the wave reaches relative to 0V.
- *Peak-to-peak voltage* (Vp-p): The maximum (most positive) value that the wave reaches relative to the minimum (most negative) value it reaches.
- *Root-mean-square voltage* (VRMS): A statistical value representing the average of the alternating voltage. This essentially represents an AC voltage as a steady, equivalent DC voltage.

- *Power* (P): This expression is common in adio communications, but differs from the other methods of expressing amplitude because rather than being an expression of voltage, it is an expression of how voltage, electric current and resistance interact in an electrical element to produce work. In a typical radio communications example, the electrical element can be an antenna, and the work produced, measured in **Watts** (W), is the electromagnetic radiation produced.

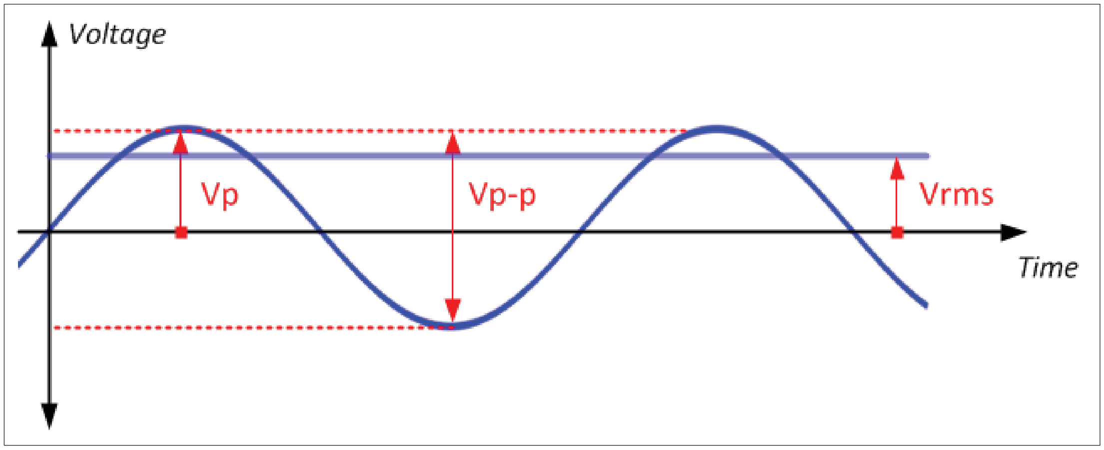


Figure 2-3: Illustration of Amplitude

***Frequency:* The** rate at which the electromagnetic wave (or anything cyclical) varies and repeats, and is measured in a unit called **Hertz** (Hz), which represents cycles / second. It is calculated by taking the reciprocal of the interval of time in seconds (called the period) that it took to return to the same state at which the cyclical event started. One (1) Hz is therefore equal to something repeating once every second; one thousand cycles is one Kilo Hertz (kHz); one million cycles is one Mega Hertz (MHz); and one billion cycles is one Giga Hertz (GHz). See Figure 2-4.

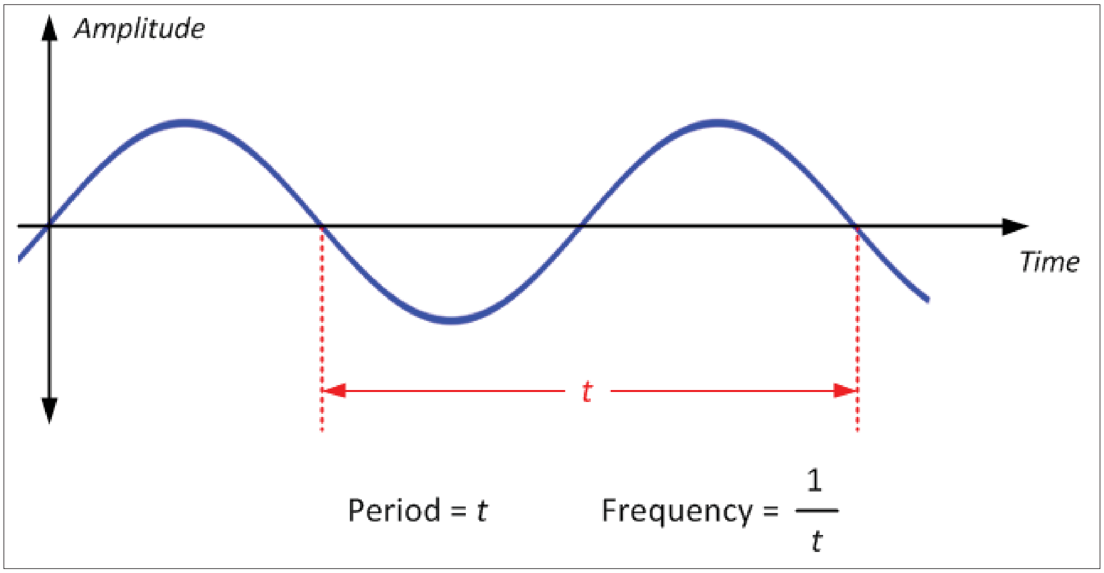


Figure 2-4: Illustration of Frequency

Phase Angle (or simply ***phase***): The trigonometric angle of a sinusoid relative to its origin. It is used to indicate a point in a sinusoidal wave using degrees (or radians) as the unit of measure. In terms of a radio wave, it is an indication of the wave's voltage relative to time. If one relates the sinusoid to rotation around a circle over time, it is easier to understand this concept.

The diagram below (see Figure 2-5) shows where a phase angle—denoted by the Greek letter theta (θ)—equal to 90 degrees, can be located on a sinusoid.

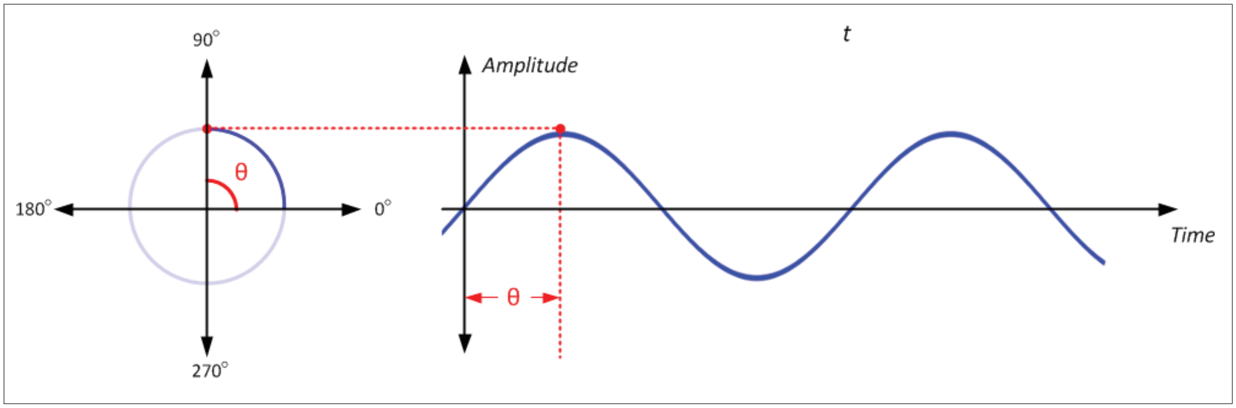


Figure 2-5: Illustration of Phase Angle

Phase Shift: Occurs when one changes the phase angle at the origin (where t = 0), thereby moving the sinusoid in time. The diagram below (see Figure 2-6) shows a phase shift of 90 degrees.

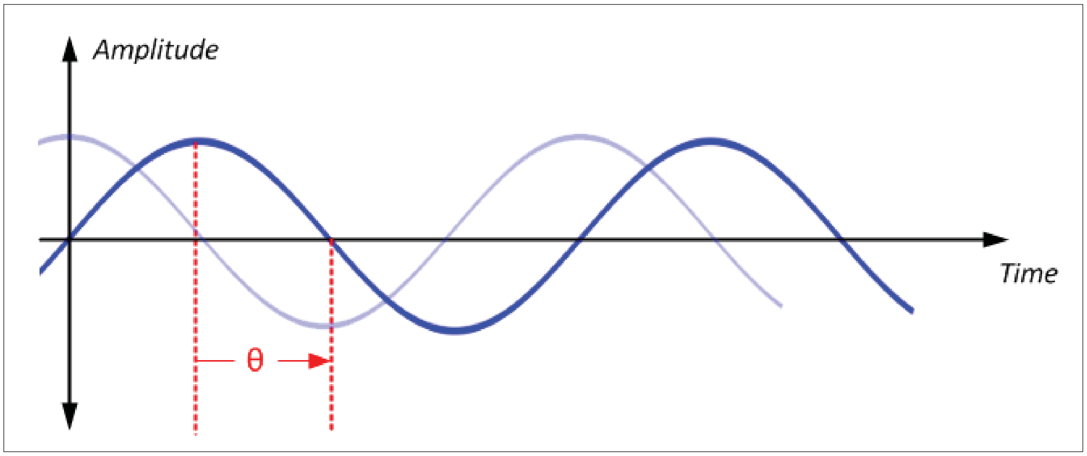


Figure 2-6: Illustration of Phase Shift

Wavelength: The physical distance between the repeating points on a radio wave travelling through the air. In terms of a radio wave, it is an indication of the wave's voltage relative to spatial distance. Wavelength is measured in meters and represented by the greek character λ. Wavelength is inversely proportional to frequency (as frequency gets bigger, this distance becomes smaller). The term microwave is often used in communications, referring to frequencies that have a wavelength on the order of 10^{-6}.

ELECTROMAGNETIC SPECTRUM, CHANNELS AND BANDWIDTH

The Electromagnetic Spectrum

Electromagnetic energy can be arranged on a linear scale according to frequency called a spectrum, ranging from 0 Hz (does not change at all) to frequencies in the order of 10^{22} (known as cosmic rays). This total spectrum is divided into smaller spectrums and useful sections known as bands, which are defined by the type of use or characteristics of the electromagnetic frequencies falling within its range (see Figure 2-7). These bands are often divided into smaller sub-bands.

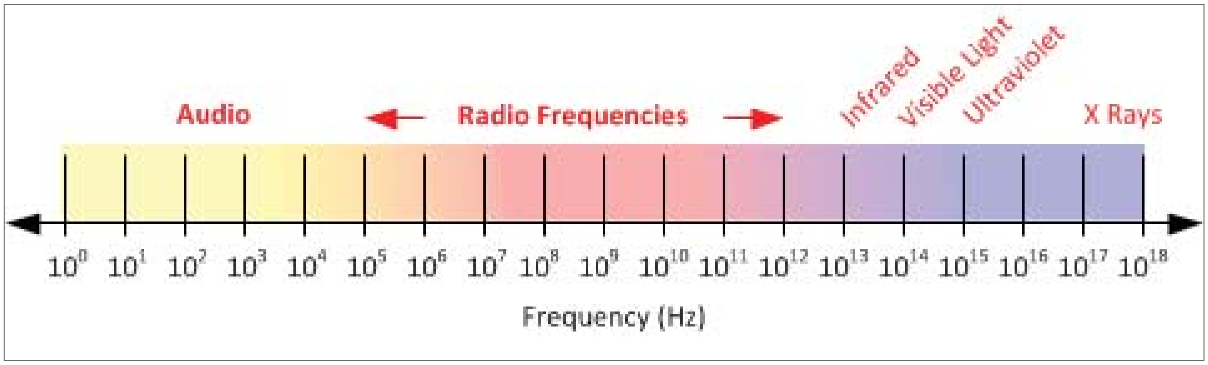


Figure 2-7: Linear Electromagnetic Spectrum

The portions of the overall frequency spectrum of particular interest in radio communication are the *Audio Frequency* (AF) spectrum and the *Radio Frequency* (RF) spectrum.

The AF spectrum consists of electromagnetic frequencies that range from approximately from 30 Hz to 30 kHz. AF signals are equivalent in frequency to the acoustic frequencies that the human ear can perceive; therefore, if you connect a wire carrying a current varying within this range of frequencies to a speaker (a device with converts electricity to air vibrations), you will be able to hear these frequencies. An important distinction to make is that although sound is also referred to in terms of frequency, it is not itself a form of electromagnetic energy until it is converted with the aid of electronic equipment.

The RF spectrum is consists of electromagnetic frequencies suitable for transmitting information over the air; they are imperceptible to the human senses but can be detected using electronic equipment. The RF spectrum is divided into the standard operating bands outlined in the table below (see Table 3).

Table 3: RF Spectrum Operating Bands

Designation	Frequency Range	Wavelength	Typical Use
Extremely Low Frequency (ELF)	3 Hz – 300 Hz	10,000 km – 1,000 km	Underwater (Submarine)
Ultra Low Frequency (ULF)	300 Hz – 3 kHz	1,000 km – 100 km	Ground (Earth-Mode)
Very Low Frequency (VLF)	3 kHz – 30 kHz	100 km – 10 km	Radio Navigation, Time Clocks
Low Frequency (LF)	30 kHz – 300 kHz	10 km – 1 km	Longwave AM Broadcast, Time, Navigation
Medium Frequency (MF)	300 kHz – 3 MHz	1 km – 100 m	Medium-wave AM, Navigation, Ship to Shore
High Frequency (HF)	3 MHz – 30 MHz	100 m – 10 m	Long Distance, Ionosphere Skip, Shortwave
Very High Frequency (VHF)	30 MHz – 300 MHz	10 m – 1 m	FM Broadcast, LMR, TV Broadcast, Marine
Ultra High Frequency (UHF)	300 MHz – 3 GHz	1 m – 100 mm	LMR, TV Broadcast
Super High Frequency (SHF)	3 GHz – 30 GHz	100 mm – 10 mm	Radar, Microwave, Cellular, Satellite
Extremely High Frequency (EHF)	30 GHz – 300 GHz	10 mm – 1 mm	Radio Astronomy

Channels

Radio signals can generally exist within the same physical space without interfering with one another provided that they differ in frequency. Thus, radio systems are allocated very specific frequencies within the operating band of the electromagnetic spectrum by regulatory bodies so they do not interfere with each other. These subsets of frequency are known as channels.

Frequency Bandwidth

The range of frequencies between the lowest and the highest frequencies that a channel (or signal within a channel) occupies is known as the frequency bandwidth (or most commonly, simply bandwidth). See Figure 2-8.

In general, the more information that one wishes to send, the higher the bandwidth that is required. However, as the frequencies that regulatory bodies can allocate become scarcer, various technologies (some of which are discussed in a later section of this text) are employed to make communications more efficient in terms of required bandwidth. The process of converting radio equipment to operate at higher bandwidth efficiency is called *narrowbanding*.

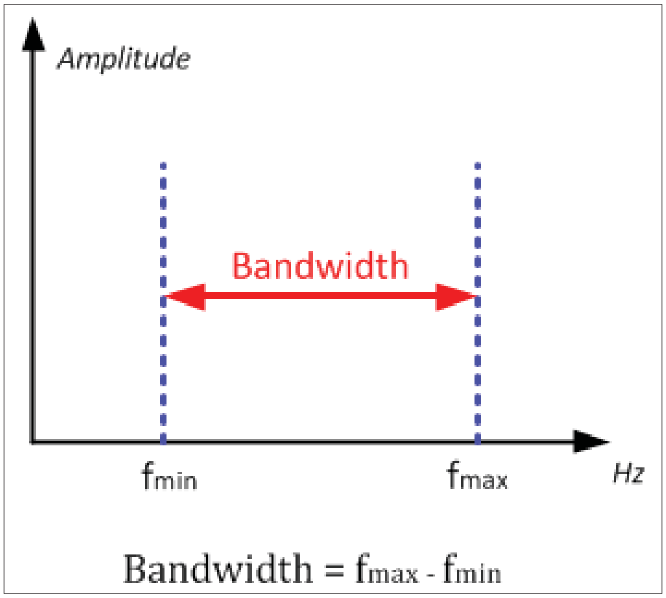


Figure 2-8: Illustration of Bandwidth

A channel will typically be of a fixed bandwidth as defined by the regulation of the radio technology being used. Typical channel sizes in LMR are 6.25 KHz, 12.5 kHz and 25 kHz. A channel will often have a small amount of frequency band reserved on either side of it to prevent interference from adjacent channels; this is known as a guard band (see Figure 2-9).

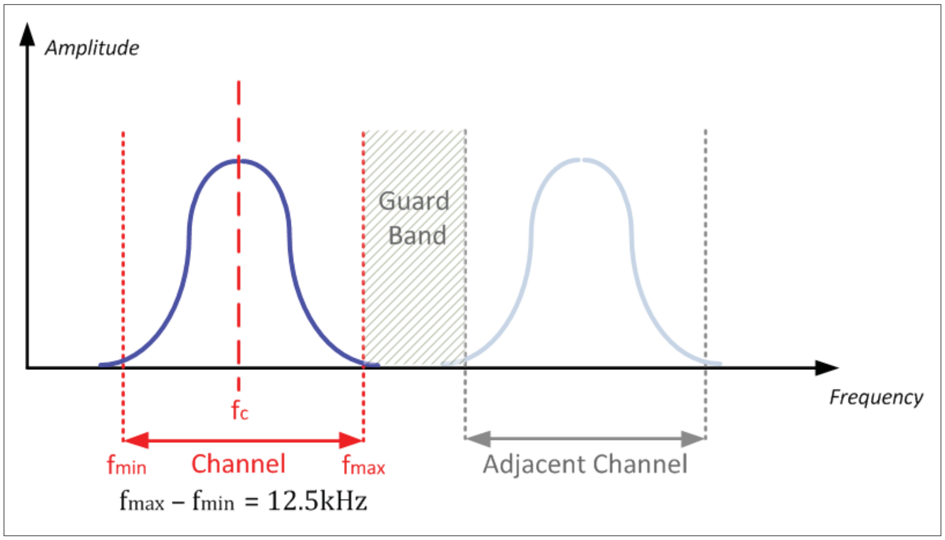


Figure 2-9: Guard Band Between Channels

A SIMPLE RADIO COMMUNICATION SYSTEM

The block diagram below (see Figure 2-10) shows the most basic type of radio communications system in which a single transmitter at one location and a single receiver at another location are separated by air.

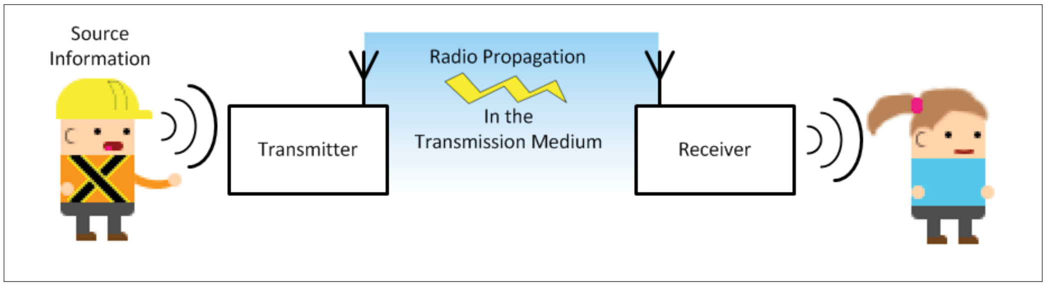


Figure 2-10: Basic Radio System

The low frequency source information is input into the transmitter where it is processed and 'imprinted' on a radio signal by a process called modulation and then radiated out as a radio signal. The radio signal travels, or propagates, through the transmission medium (the air) until a receiver resonates with its frequency—discerning it from all the other RF energy in the air—and 'extracts' the intelligible information via a process called demodulation; after which the radio signal is output for the 'listener'.

While a single transmitter often reaches multiple receivers, for the sake of understanding these concepts it is best to think of a single transmitter and a single receiver separated in distance by air. This simple arrangement is known as a radio communication link (see Figure 2-11).

These concepts are explored in greater detail in the next sections.

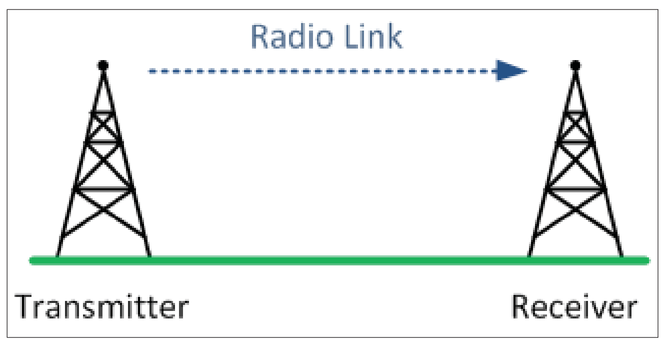


Figure 2-11: Simple Radio Link

SOURCE INFORMATION

Source information is the message that we are trying to communicate to our recipient(s). This information can come in many forms that ultimately fall into two categories: analog and digital.

Analog Signals

Information signals vary continuously over time, and when converted to an electrical signal, produce an infinite number of possible voltage values between the two extremes. For example, when a person speaks into a microphone, there is an element inside the device that converts sound vibrations into corresponding voltages. The result is an electronic waveform that varies between two limits in time with the person's voice (see Figure 2-12). The voltage value of this waveform can take on any possible value, provided it falls between the set limits of the device.

Figure 2-12: Sound to Wave Signal

Digital Signals

Digital communication is most often associated with new technologies, but the earliest digital format, Morse Code, was actually the first to be applied to radio communication decades before analog voice communication appeared.

Unlike analog signals that can have any possible value, these signals can only take on one of a finite number of values at any given time. Most often, digital signals are **binary**, which means that they can be one of two possible values: a '1' or a '0'. These ones and zeroes are each represented by a discreet voltage level; typically a '1' is represented by +5V and a '0' is represented by 0V.

Each individual '1' or '0' is called a bit. These bits are grouped together into group of 8 (also known as a byte), 16, 64 or any other number obtained by making an exponent with a base of two (2n), since there are two states: '0' and '1'. These groups of bits are used to represent larger numbers, letters or other meaningful information. Below is an example showing how binary numbers are used to represent the numbers zero through seven.

Table 4: Decimal vs. Binary

Decimal Number	Binary Number
0	000
1	001
2	010
3	011
4	100
5	101
6	110
7	111

Electronic systems, including communications systems, most often handle these bits one at a time in what is called a *bitstream,* making timing an essential part of any digital system. The rate at which the bitstream is processed is called the *bitrate* (see Figure 2-13) and is measured in *bits-per-second* (bps). Bitrates are usually large in magnitude and use metric prefixes to simplify notation: kbp indicates bitrates in the order of a thousand bits-per-second, Mbp in the order of one million bits-per-second, and so on.

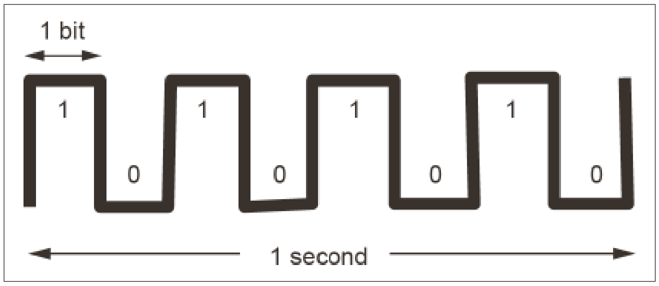


Figure 2-13: Bitrate

An important fundamental concept to understand is that each bit represents information. A single bit can represent a “Yes” or “No”, an “Off” or “On”, or any other information that can take more states. The more bits that you combine together, the more complex and detailed the information that can be represented. With 26 bits, for example, you can represent the English alphabet.

The flexibility of using bits to represent information, is that it allows one to convey information very efficiently. Once again returning to the most basic example of using a single bit to represent “Yes” or “No”; if one were to speak the word “Yes” into a microphone, it takes about a half second and requires a full range of voltages to represent the sound. A bit on the other hand can be sent in a tiny fraction of a second and requires only two voltages to get the message across.

The advantages of digital signals are also not limited to efficiency. Analog signals are often converted into digital signals because they are easier to use with computer systems and they are able to resist the effects of noise. While some information is lost in the conversion—since digital signals cannot account for every analog level—the result is often indistinguishable, and even better, unwanted parts of the analog signal can be removed in the process.

Subtones

Not all source information signals are audible or meant for translation for human understanding. Some information can be added that is meant as instructions for the receiving equipment on how to operate or which radio signal to listen for. These signals, called subtones, are electrical signals that are often of a frequency that is too low to be heard by the human ear when applied to a speaker.

The practical application of these signals is described later in this text.

DTMF

DTMF stands for Dual-tone multi-frequency and it is the basis for a telephone system. DTMF is actually the generic term for Touch-Tone (Touch-Tone is a registered trademark of ATT). When you press the buttons on the keypad, a connection is made that generates two tones at the same time. A “Row” tone and a “Column” tone as shown in Figure 2-14. These two tones identify the key you pressed. When you press the digit 1 on the keypad, you generate the tones 1209 Hz and 697 Hz. Pressing the digit 2 will generate the tones 1336 Hz and 697 Hz.

1	2	3	A	697 Hz
4	5	6	B	770 Hz
7	8	9	C	852 Hz
*	0	#	D	941 Hz
1209 Hz	1336 Hz	1477 Hz	1633 Hz	

Figure 2-14: DTMF Tone Chart

DTMF signals can be easily transmitted over a radio system, as all of the tones are in the standard audio frequency range (300 – 3000 Hz). A DTMF code (sequence of numbers) can be sent over the radio system and a corresponding DTMF decoder can detect the appropriate code and then be used to turn devices on or off, to allow for remote signaling, operating lights, relays or alarms.

TRANSMISSION

The function of the transmitter is to interpret the source information, which is in the form of a low-frequency electronic signal, and 'imprint' it on a high frequency carrier signal that can travel long distances over the transmission medium to the receiver.

Although transmitters are often complex electronic devices, their operation can be summarized by the following functional stages (see Figure 2-15):

1. Audio Processing
2. Frequency Generation
3. Modulation
4. RF Amplification
5. Antenna

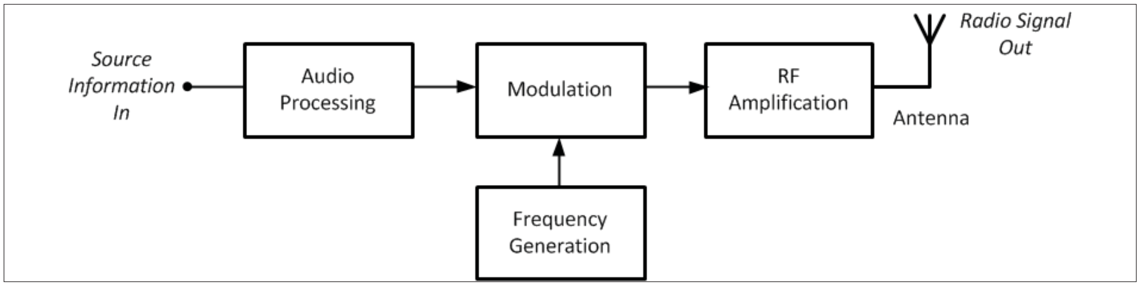


Figure 2-15: Transmitter Block Diagram

Audio Processing

The first function of the transmitter is to take an external form of source information and convert it to electrical signals that can be used within the transmitter.

Audio Conversion and Analog Signal Processing

Analog information is most often created when sound pressure waves (for example, person's voice) are applied to a microphone; an element within the microphone vibrates in step with the sound; and the sound is converted into an analog audio electrical signal.

In converting sound into an electrical signal, there are some parts that are unwanted as they do not convey intelligible information. Also, since the human voice (or other sounds) can vary to an almost infinite degree in magnitude and frequency, some compensation must be made in order to work within the limitations of the electronic transmitting equipment.

Therefore, the audio signal is processed after it is introduced into the transmitter to eliminate or enhance frequency and amplitude characteristics and make the signal ready for transmission.

In a process called *companding*, the audio signal can be *amplified* (made stronger) or *attenuated* (made softer) depending on the volume of the speaker's voice. This process ensures that quiet (small) signals get included in the transmission and that loud (large) signals do not get distorted by the electrical equipment.

Audio filters are used to eliminate the extreme high and low audio frequencies that fall outside of the typical range of human hearing, as well as other unwanted frequencies that can be considered as noise in an audio signal.

Shaping circuits make the higher audio frequencies greater in amplitude to improve the modulation process that follows. This process is called pre-emphasis since it emphasizes the higher frequency audio signals.

The addition of subtones and other control signals also occurs in the signal processing stage.

Analog-to-Digital Conversion and Digital Signal Processing

Quite often, analog signals will be converted into digital information within the transmitter before being sent, and converted back to analog audio upon being received by the receiver. This process, known as *Analog-to-Digital Conversion (ADC)*, is advantageous because the process eliminates noise inherent in the analog signal and allows for error detection and correction capability.

The conversion process involves first *sampling* the analog signal (i.e., determining the instantaneous voltage level value at regular discreet intervals), then quantizing the samples by assigning a weighted binary value to voltages depending on where they fall within pre-determined voltage ranges (this process is called *quantization*). The result is a stream of binary bits representing the original analog waveform. See Figure 2-16.

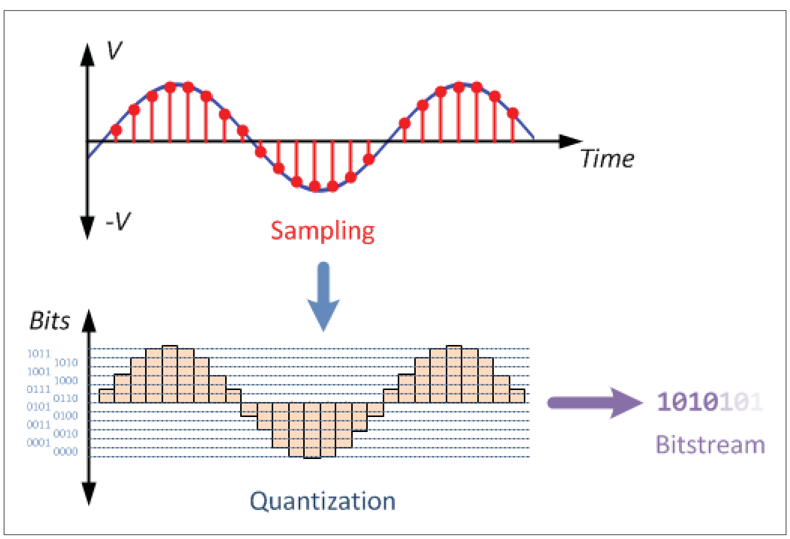


Figure 2-16: Analog-to-Digital Conversion Process

Once the signal is converted from analog to digital (or a digital signal is input directly into the transmitter), a *Digital Signal Processor (DSP)* can perform functions that are equivalent to the companding, filtering and shaping functions in analog processing. The DSP can also introduce additional error detection and correction information into the signal that tells the receiver that the signal it has received is free of error.

Frequency Generation

While the AF signal is generated by the user's voice and the audio processing circuitry, a device called an oscillator generates the high-frequency RF signal. When this device is internal to a piece of equipment like a transmitter (or receiver), it is often referred to as the *Local Oscillator (*LO).

Oscillators

The oscillator device is used to produce a high frequency electrical sinusoidal waveform (see Figure 2-17).

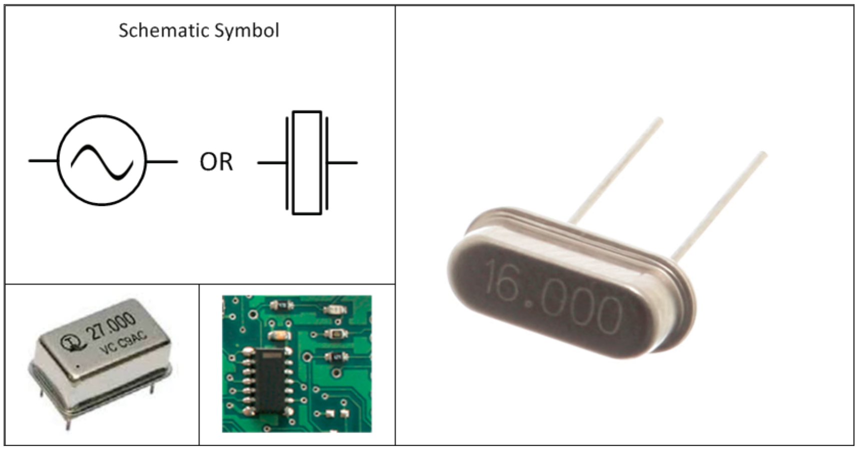


Figure 2-17: Oscillators

The key performance metric in an oscillator is frequency stability, which is the ability of the oscillator to produce and sustain a signal of precise frequency. Often the frequency produced by the oscillator can be externally varied by applying an external control such as voltage (this is useful for devices that operate on multiple frequencies).

There are various types of oscillators employing different technologies depending on application and constraints (such as cost). The two most commonly used in basic radio applications are:

1. **Voltage Controlled Oscillators *(VCO)***: a device made of various electronic elements that produces a signal whose frequency can be controlled / varied by applying an external DC bias voltage.

2. **Crystal Oscillators**: a device that uses a special type of crystal that generates a very precise electrical signal when mechanical pressure is applied. This is known as the *piezoelectric effect*. Crystal oscillators are susceptible to reduced frequency stability with changes in temperatures, so they are often compensated using electrical circuits. These devices are known as *Temperature Compensated Crystal Oscillators* (TCXO).

Carrier Signal

The basic RF signal produced by the oscillator in a transmitter is known as the *carrier signal*. The carrier signal is simply a sinusoidal (time-varying) electrical signal that has a frequency in the RF range. The frequency of the carrier is the frequency that the device is set to operate at (i.e., if you have a transmitter operating at 450 MHz, the carrier signal is oscillating at 450 MHz).

The carrier is the signal that the receiving equipment is designed to "listen" for, but in itself it does not contain any information; the information must be added to the carrier by a processed called **modulation**.

Modulation

Modulation is the process of 'imprinting' the low-frequency source information signal on the carrier signal by changing its properties.

As with any sinusoidal signal, the carrier signal has three properties that can be varied:

1. **Amplitude:** the voltage magnitude of the carrier signal.
2. ***Frequency*:** the rate at which the signal varies with time.
3. ***Phase (or angle)*:** the relative trigonometric phase angle of the signal.

The type of modulation is defined by which of these attributes of the carrier signal are modified by the application of the source information. The type of modulation used is the key defining characteristic of the transmitter and by extension the radio system.

Amplitude Modulation

In a transmitter employing *amplitude modulation* (AM), the amplitude of the carrier signal is varied in time with the amplitude of the source information. This process in the time domain is shown below (see Figure 2-18).

NOTE: Image is courtesy of Wikimedia Commons

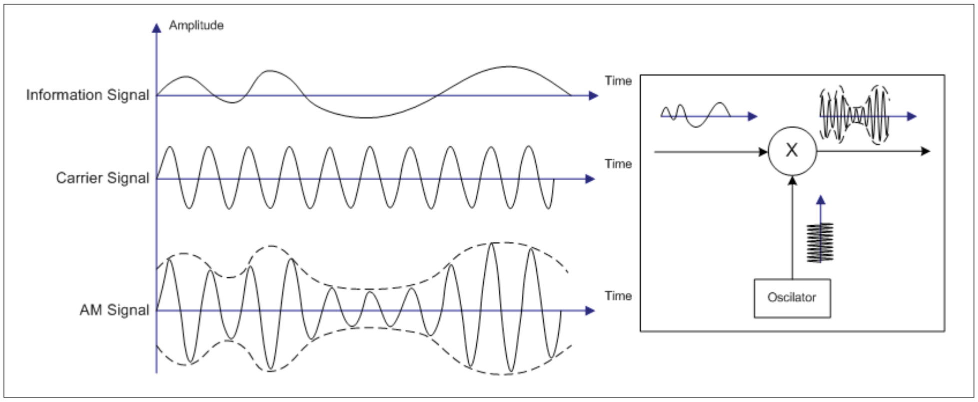


Figure 2-18: Amplitude Modulation Process

Note that the amplitude of the carrier signal takes on the shape of the source signal, but the frequency of the carrier signal remains constant. The shape of the source signal is also mirrored on the negative portions of the carrier wave. The overall positive and negative shape that limits the amplitude the carrier signal is called the *envelope*.

The process by which the source signal is applied to the carrier signal is called *frequency mixing*, and in it the two signals are essentially multiplied together using non-linear electronic devices. This process has a by-product in the form of additional, less powerful signals above and below the carrier frequency. While these frequencies, known as *sidebands* (SB) are generally unwanted as they occupy more bandwidth, there are some radio applications in which they are used to convey information as well.

When viewed in the frequency spectrum, an AM signal appears as shown (see Figure 2-19).

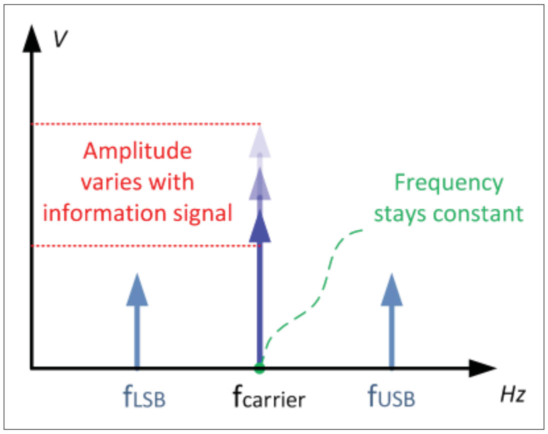


Figure 2-19: AM Signal in Frequency Spectrum

Although AM radio systems are increasingly more rare due to the spread of frequency modulation technology, there are still many applications that use AM radio, such as commercial broadcast radio, marine and aircraft communications. The table below (see Table 5) summarizes the advantages and disadvantages of AM radio.

Table 5: AM Radio Comparisons

Advantages	**Disadvantages**
Inexpensive equipment	Poor sound quality
Is able to travel far with less power	Susceptible to noise and interference
Requires little bandwidth	

Frequency Modulation

In a transmitter employing *frequency modulation (FM),* the frequency of the carrier signal is varied in time with the amplitude of the source information.

Note that the frequency of the carrier signal increases and decreases, but the amplitude of the carrier signal remains constant (see Figure 2-20).

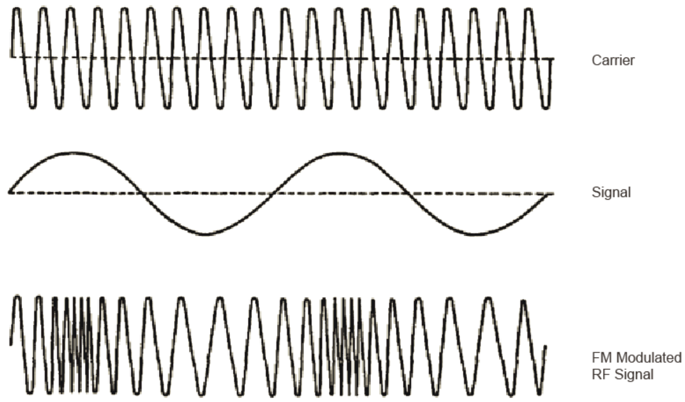


Figure 2-20: Frequency Modulation Signal

When viewed in the frequency domain, an FM signal appears as shown below (see Figure 2-21).

The center line is the carrier frequency and the occupied areas to either side of it represent the possible frequencies that can occur as the carrier is varied with the source information. This is why FM requires more bandwidth; the more the signal varies, the more possible frequencies need to be made available, thus the required channel size grows.

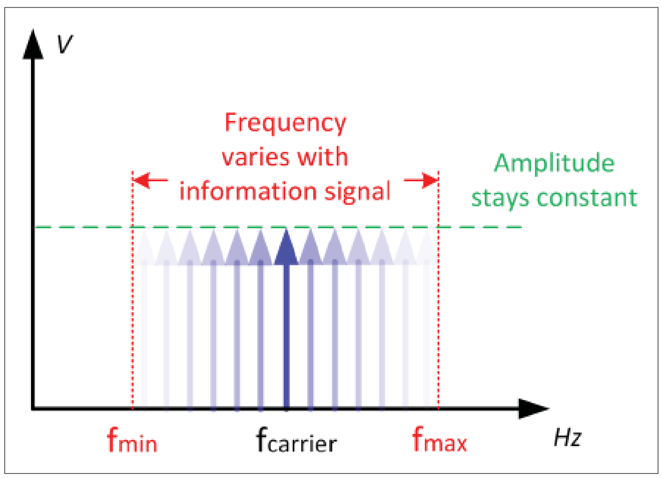


Figure 2-21: Carrier Frequency Graph

The variation of the signal from the carrier frequency is known as the *frequency deviation* of the signal. This is limited within a transmitter to ensure that the transmitted frequency does not go outside of its designated channel.

FM is currently the pre-dominant choice of technology in radio communications and, with the reduction of price in FM electronics, this trend is likely to continue. The table below summarizes the advantages and disadvantages of FM Radio over AM radio (see Table 6).

Table 6: FM Over AM Comparison

Advantages	Disadvantages
Less prone to interference	Requires a high bandwidth
Better sound quality upon reception	Lower range and requires more power
	Equipment is more expensive

FM is typically implemented by using the modulating signal as a control voltage for the VCO.

Phase Modulation

Phase modulated (PM) signals are extremely similar to FM signals because the phase and frequency of a signal are mathematically related to one another. That is, when the frequency is varied in an FM signal, the phase of that signal is indirectly varied and vice versa. Therefore, the only difference between the two is which aspect you are varying directly and which you are varying indirectly.

When viewed in the *time-domain*, the signals are identical except for how they relate to the source information in time. In the *frequency domain*, since frequency is changed with phase, the signal looks exactly the same as an FM signal.

The variation of the carrier frequency phase in time with the source information is known as the **phase deviation** of the signal.

Digital Forms of Modulation

The descriptions of modulation schemes given above all used analog source information. For digital source information, the carrier signal is also varied in amplitude, frequency or phase, but the variation is rapid rather than gradual with a bit being mapped to a particular amplitude, frequency or phase.

The most simple, low performance form of digital modulation is called *keying*, in which a single bit of the information signal is represented by a quick change in characteristic in the carrier signal.

- **Amplitude Shift Keying (ASK):** The amplitude of the carrier is higher for a "1" bit and lower for a "0" bit. The most extreme form of this is called *On-Off Keying* (OOK), in which the carrier is turned off (reduced to 0V) to represent a binary "0". See Figure 2-22.

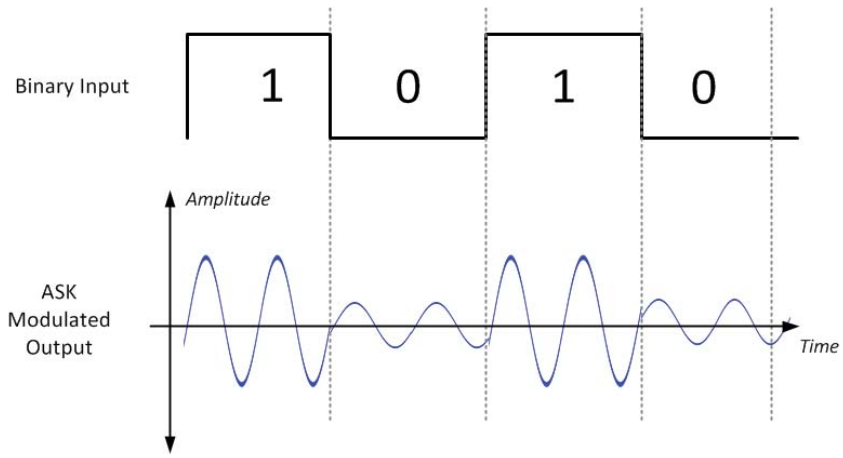


Figure 2-22: ASK Modulation Diagram

- **Frequency Shift Keying (FSK)**: The frequency of the carrier is deviated to its maximum for a "1" bit and deviated to its minimum for a "0" bit. See Figure 2-23.

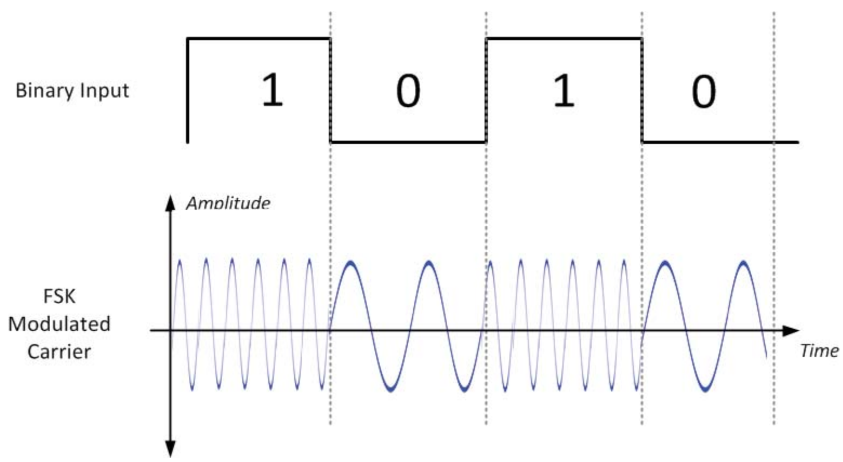


Figure 2-23: FSK Modulation Diagram

- **Phase Shift Keying (PSK) or Binary Phase Shift Keying (BPSK)**: The phase of the carrier is shifted by 180° for a “1” bit and remains at 0° for a “0” bit.

More advanced forms of PSK combine groups of bits together and assign them a corresponding phase. In doing this, the transmission of data becomes faster because a single change in phase can represent a larger number of bits and by extension information. For example, *Quaternary Phase Shift Keying* ***(QPSK)*** uses four different phases (45°, -45°, 135°, -135°) to represent four different combinations of bits (00, 01, 10, 11); 8-PSK uses eight different phases to represent eight different combinations of bits, and so on. See Figure 2-24.

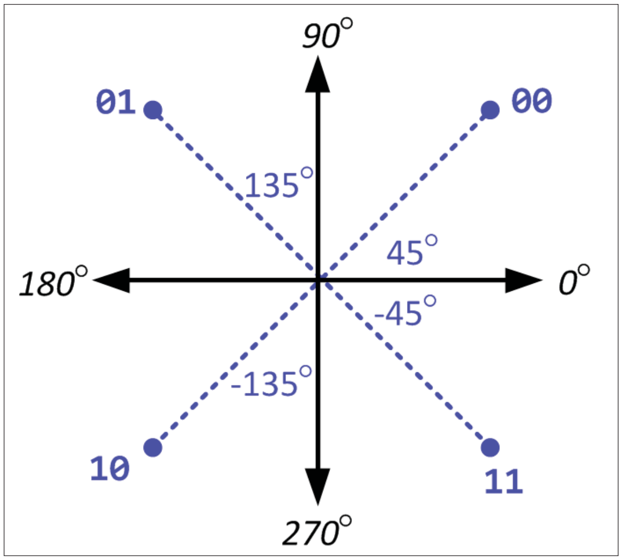


Figure 2-24: QPSK Phases

Even more advanced forms of digital modulation schemes, called *Quadrature Amplitude Modulation (QAM)*, combine both phase and amplitude modulation to represent combinations of bits, making the transmission of information even more efficient. For example, *8-QAM* uses four different phases in combination with four different voltages to represent eight different combinations of bits.

RF Amplification

The signals within a transmitter are relatively weak (low in voltage / power) since smaller signals are easier to work with in the initial stages of conversion and modulation; however, in order to have the modulated RF carrier signal travel long distances, one must make them stronger in power through a process called amplification.

Amplifiers

Electronic devices and/or equipment called amplifiers perform the process of signal amplification by re-creating the shape of a small voltage time-varying input signal with a larger voltage power supply (see Figure 2-25).

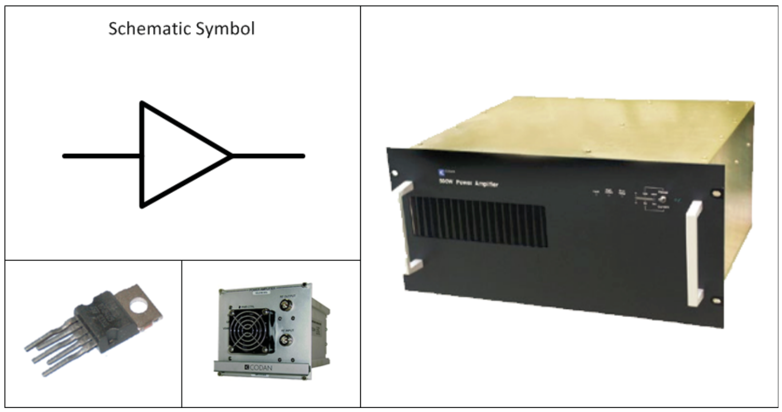


Figure 2-25: Amplifiers

The operation of an amplifier is characterized by a number metrics, the most important of which are:

- **Gain**: the amount a signal increases in power or voltage between the input of the amplifier and the output. Gain is the key defining characteristic of an amplifier. It is in essence a unitless number representing the ratio between the input and output voltage, current or power; so one can simply take the voltage at the input, for example, and multiply it by the gain to determine what the voltage at the output would be.

  However, in practice it is most often represented in decibels (dB or dBm) relative to input. This is done so that gain can be more conveniently calculated in the situation where there are multiple amplifiers (or other elements that have gain) arranged one after another.

- **(Frequency) Bandwidth**: the range of frequencies that the input signal can have for the amplifier to work correctly and not be damaged. Amplifiers are devices that are sensitive to frequency. If a frequency is input that falls outside of the amplifier's operating bandwidth, it may either not be amplified to the level that is expected, or in extreme cases, may cause the amplifier to become unstable and oscillate, thus creating a large unwanted output that can damage the amplifier and other equipment connected to it.

- **Noise**: how much noise is added to the output signal during the amplification process. Since the amplifier is taking a small signal and "converting" it to a larger signal, it may also take some unwanted voltages in the circuit and make them larger as well. These unwanted voltages, caused by random electronic effects or external signals leaking into the circuit, are normally too small to be noticed, but when amplified can be problematic and can damage the overall quality if the intended signal.

- **Efficiency**: how efficiently the input signal is amplified to the output signal and how much power is lost in the process in the form of heat or other factors
- **Linearity**: how proportional the output signal is to the input signal. Ideally, the output signal would be completely proportional to the input signal; that is, the shape of the output signal would be exactly the same as the input signal, only larger in magnitude. In practice, the electronic devices used in the amplification process are overall non-linear and only have a range of voltages in which the input and output behave proportionally.
- **(Input/Output) Dynamic Range**: the smallest and largest signals that can be input / output by the amplifier. The *input dynamic range* defines what signal is too small for the amplifier to discern and make larger, and how large an input signal can be before the amplifier can no longer make it larger without distorting the signal. The *output dynamic range* defines the smallest and largest signals produced at the output by the amplifier. In essence, this is the voltage equivalent to the frequency bandwidth.
- **Time Response**: since the amplification process is not instantaneous, there are a number of time factors that need to be considered, such as how quickly the output signal changes with respect to the input signal, or how quickly the input signal can change before the amplifier can no longer keep up with changing the output signal (known as the Slew Rate)

Amplifiers can take many forms, from tiny integrated circuits within a transmitter (or other electronic equipment) to a very large, standalone pieces of equipment, depending on their use and the amount of power they are expected to output.

It can be generally assumed that a transmitter will have some form of amplifier built-in, as it is an essential part of transmitter operation. Additional amplifiers are often connected to the output of the transmitter to further boost the power of the transmitted signal. The addition of one or more amplifier to an output of a preceding amplifier is called *cascading* and each individual amplifier within such a system is called a *stage*. While cascading amplifiers increases the overall output power, care must be taken that the input and output signals of each stage do not exceed regulatory limitations and the capabilities of the other equipment in the system.

Antenna Interface and Transmission

The final stage in the transmission process is to transfer the modulated and amplified RF carrier signal from the transmitting device to the air via a metallic electrical conductor system called an *antenna*. To understand this process, we must first address the important topic of impedance and how it affects the transfer of electrical power from one place to another.

Impedance Matching, VSWR and Reflected Power

Impedance is the apparent electrical resistance of elemental electronic components (i.e., resistors, capacitors and inductors) when high-frequency signals are applied. The elements within a high-frequency electronics device, such as a receiver or transmitter, have to be impedance matched to ensure that the high-frequency electrical signal gets transferred from one element or circuit to another as efficiently as possible.

In a properly impedance matched circuit all of the power in the electrical signal is transferred from the output element (commonly referred to as the *source*) to the input element (commonly referred to as the *load*) without loss. The time varying electrical signal that gets transferred is called the *incident wave*. When the impedance of the source does not match the impedance of the load, some of the power of the incident wave is reflected at the junction of the two elements back into the output element, producing a *reflected wave*. The energy that is transferred from the incident wave is called the *coupled energy*. See Figure 2-26.

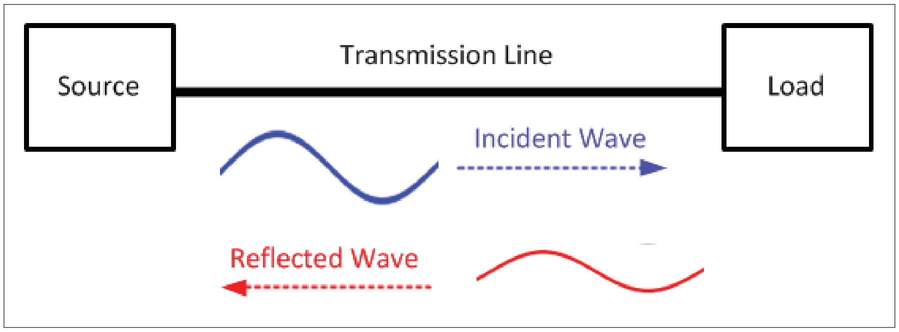


Figure 2-26: Coupled Energy

The ratio between reflected power and incident power is the *Voltage Standing Wave Ratio (VSWR)*. The ideal condition is when VSWR = 1, which means that the all incident energy is transferred and nothing is reflected. One will often find a VSWR rating on radio communication, which should be as close as possible to 1, keeping in mind that a perfect VSWR is hard to achieve in practice.

The pertinent example of this is the attachment of an antenna (the electrical load) to the transmitter amplifier (output source). If both the output of the amplifier and the antenna are functioning properly and have the same rated impedance (typically 50Ω), the VSWR at the junction between the two will be approximately equal to 1, and the full power of the transmitter will be transferred to the antenna and transmitted.

If the antenna is faulty and does not have an input impedance of 50Ω, the VSWR will be greater than 1 and some of that power will be reflected back into the amplifier instead of being transmitted; this will not only limit the transmission of the signal, but will most likely damage the amplifier as well.

The Antenna

Antennas can take many shapes, sizes and configurations depending on a number of factors, for example (see Figure 2-27):

- wavelength of the signal that they will be transmitting (and/or receiving)
- power of the signal
- space available for their deployment

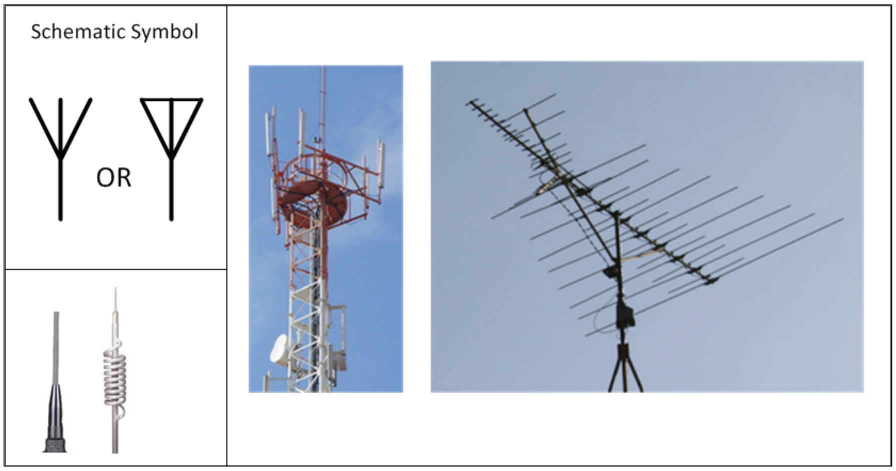


Figure 2-27: Antennas

While this may seem complicated, antennas are essentially any type of conductor that is conducive to transmitting a radio signal. An antenna is simply an electrical circuit that is open (i.e., disconnected at a point from being a complete circuit), which is why the simplest antenna can be made of just one (called a *monopole*) or two (called a *dipole*) pieces of wire.

The open in the circuit means that it has an impedance and VSWR of ∞ and while this usually is a worst-case scenario in a circuit, in the case of an antenna its ideal. As an incident wave hits the abrupt discontinuity, a portion of the energy is transferred into the air as an electromagnetic wave; the rest is reflected back and remains in the antenna as a standing wave and/or is dissipated as heat.

Many antennas are the size of a quarter-wavelength or half-wavelength of the intended signal to take advantage how a wave travels within the antenna, thus maximizing the transfer of energy into the air. Recall that wavelength is inversely proportional to frequency, so the lower the frequency, the longer the wavelength and subsequently, the antenna. For example; high frequency, low power devices, such as cellular phones, have tiny antennas built into the casing of the phone, whereas lower frequency HF (skywave) communications generally require very large lengths of wire arranged on poles, such as the one shown below (see Figure 2-28).

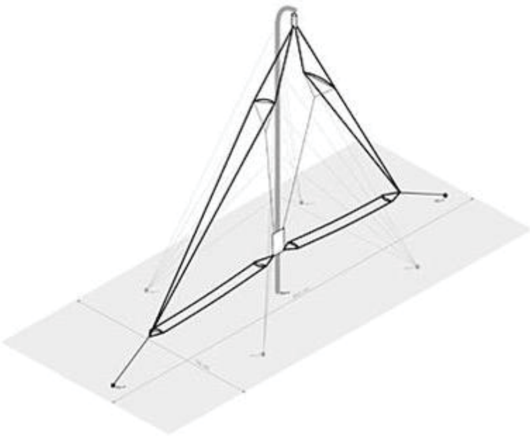


Figure 2-28: Complex Antenna

Radiation and Antenna Gain

As the electromagnetic waves leave the antenna, they radiate out in all directions. One can imagine the leading edge of the electromagnetic waves forming a single “surface” called the *plane wave*, expanding out from the antenna in all directions like a balloon being rapidly filled with air. In the simplest case, this expansion is uniform in all directions. An antenna that exhibits this behavior is known as an *isotropic antenna* or *omni-directional* antenna. In many situations, however, the aim is not to transmit in all directions, but in one direction in particular (see Figure 2-29). Using a directional antenna, one can focus the electromagnetic energy so that more goes in the intended direction and less in unwanted directions.

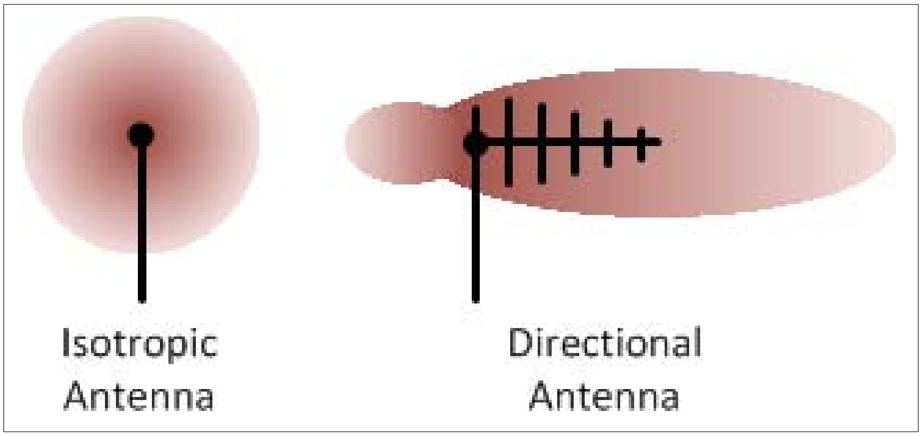


Figure 2-29: Antenna Plane Waves

Focusing the radiation of the electromagnetic energy in a certain direction is known as *gain*. Although the term ‘Gain’ is the same as is used in an amplifier, an important distinction must be made. The gain in an antenna does not actively increase the power transmitted like an amplifier does, but rather focuses more power in a particular direction at the cost of decreasing power in all other directions.

Therefore, when referring to gain in an antenna, it is a comparison as to how an isotropic antenna radiating the same amount of power would perform, rather than any amplification of the signal. Antenna gain is expressed in decibels (dB); the logarithmic ratio of the output power of the directional antenna relative to an isotropic reference antenna.

The gain of an antenna is often shown on a chart known as a *radiation pattern*; at the center point of the chart is the antenna itself and the line drawn around shows the gain in all relative directions represented by (polar) degrees. See Figure 2-30.

An antenna often has two or more of these radiation pattern charts to define its operation, for example, a horizontal one showing the ration pattern as if one were looking at the antenna from the top down and a vertical radiation pattern is if one were looking at the antenna from the side.

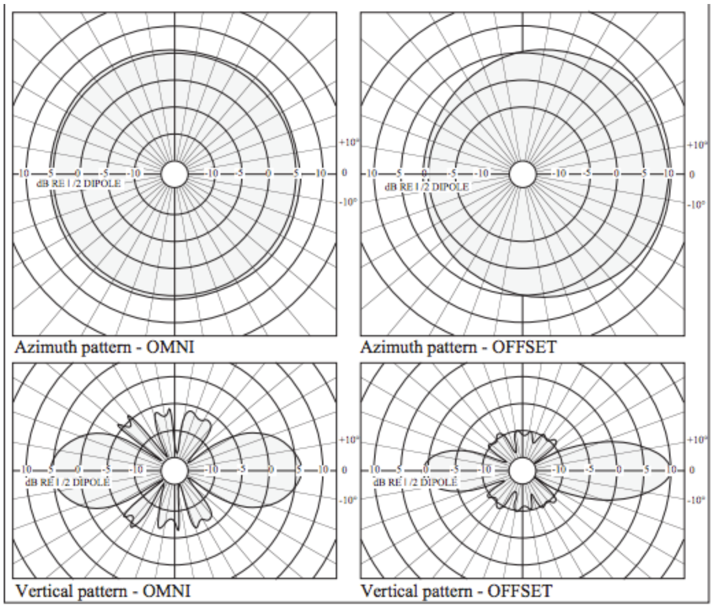


Figure 2-30: Antenna Radiation Patterns

Elongated areas of directional antenna gain extending out from the antenna are known as *lobes*. Even if an antenna is designed to have one purposeful main lobe, it will have an unintentional back lobe (see Figure 2-31).

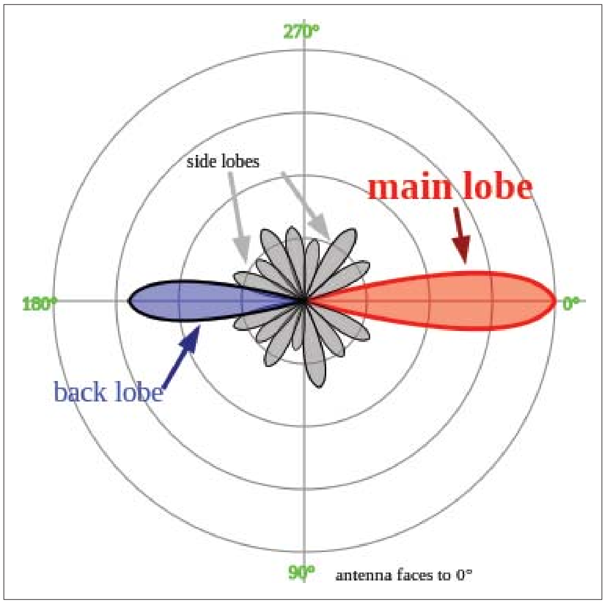


Figure 2-31: Antenna Lobes

Transmission

The transmission process is completed with the modulated RF carrier signal radiating from the antenna into the transmission medium.

PROPAGATION AND THE TRANSMISSION MEDIUM

The transmission medium can technically be anything an electronic communication signal passes through to reach its destination, but since our topic is wireless communication, we will focus on how a radio signal travels through the air to reach its destination at a receiver.

Propagation

The movement of radio waves through the air is called *propagation* and in free space (i.e., in a vacuum where nothing impedes movement) radio waves can travel at the speed of light, approximately 3x108 m/s.

Recall that the antenna on a transmitter sends out RF energy in all directions. Some radio waves will travel straight parallel to the Earth's surface; some will travel up and out in the direction of space; some will travel down towards the surface of the Earth. When viewing radio communication from this perspective, there are three categories that all types of radio communication can be grouped into:

- **Space-Wave Communication**: The typical scenario in which the transmitter and the receiver are within a *line-of-site* (LOS) of each other (i.e., the operator of the transmitter can see the receiver and vice versa) and the intended signal is sent straight through the air from the transmitter to the receiver. Most terrestrial communications, including LMR, fall into this category.
- **Ground-Wave (Surface-Wave) Communication**: Certain types of radio waves can travel along the surface of the Earth, or more ideally, salt water, since the latter is a good conductor. This form of radio communication is rarely used, though it has some application in marine communications.
- **Sky-Wave Communication**: Radio waves are projected upwards and reflected off of the Earth's atmosphere in order to achieve communication over very large distances that would normally be impeded by the curvature of the Earth (see Figure 2-32).

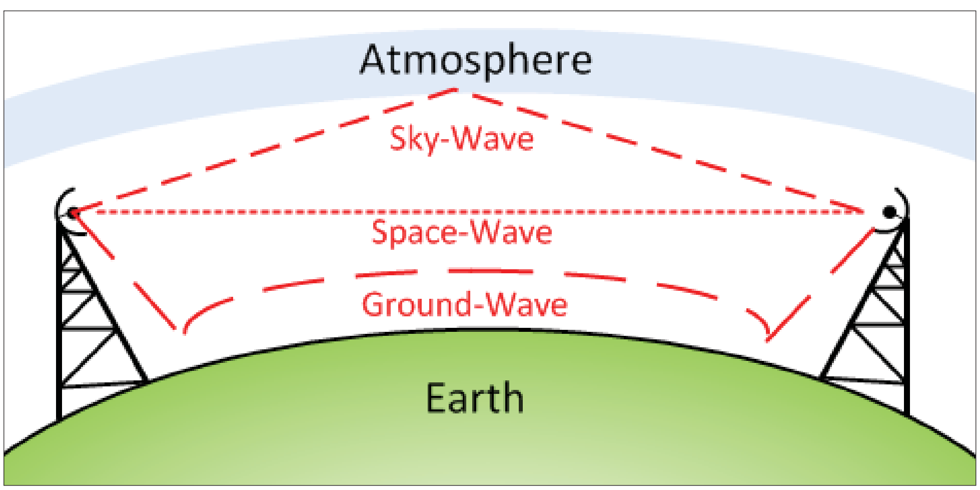


Figure 2-32: Radio Wave Communications

In practical situations the environments in which radio waves propagate are not ideal, so there are many factors that determine if a radio signal originating at the source transmitter can propagate through the air and be received at its destination:

- Placement of the transmitter and receiver
- Frequency of the signal
- Power at which the signal is transmitted
- Nature of the terrain and atmosphere between the transmitter and receiver
- Obstructions between the transmitter and receiver

The Effect of Frequency on Propagation

The frequency and wavelength of the radio waves determines how far they can travel and how they behave when they encounter an obstacle. Radio waves have a tendency to either 'bounce off' a surface, or 'pass though' (be absorbed) a surface to varying degrees, depending on the frequency of the signal. This behavior is also seen in visible light, which is also a form of electromagnetic energy. Because of this, the frequency band one chooses for their radio system must not only adhere to cost and regulatory constraints, but must also be suited for the terrain in which the system is to be used, and the distance which it must cover.

As the frequency of a radio signal increases, the less the radio wave reflects off of surfaces and the more it is absorbed by surfaces. As such, the higher the frequency of a communication system, the lower the range. Once again, thinking in terms of other common forms of electromagnetic energy is useful for remembering this concept. Visible light has a frequency in the 10^{14} Hz range and reflects off the skin, whereas x-rays (another form of electromagnetic energy) are higher in frequency at 10^{18} Hz and pass easily through one's skin, allowing doctors to take pictures of a person's bones.

Absorptive properties of radio signals are damaging to the range of radio signals. Where lower frequency signals are more likely to bounce around and eventually reach their destination, higher frequency signals will simply be absorbed by the terrain and/or the air itself and be lost altogether; this is called *absorption loss*. As a general rule, the higher the frequency that a radio system operates at, the lower the distance that its signals can travel.

Reflective properties of radio signals (including refraction, diffraction, and scattering) can either impede or assist communications. Sky-wave communication systems use the fact that HF (3 MHz to 30 MHz) radio signals can reflect and refract off of the Earth's ionosphere to overcome obstacles (such as the curvature of the Earth) to achieve communication over large distances. Space-wave communications can utilize natural or man-made reflective surfaces within the terrain to reach receivers that are outside of the LOS. Conversely, space-wave transmissions are also often impeded by properties of radio signals, since the intended signals can be kept from reaching their intended destination by reflecting in an unwanted direction or by being absorbed by an obstructing surface.

Addition of Signals and Multi-Path Loss

Another destructive effect due to the reflective properties of radio signals is called *multi-path loss*, in which reflected signals arrive at the destination receiver slightly delayed in relation to the direct intended signal because they took a less direct path (see Figure 2-33). When this happens, the direct signal and the delayed reflected signal have a tendency to cancel each other out, thus weakening or distorting the received transmission. Conversely, if the signals arrive at the exact same time, the effect is not destructive, but rather an overall strengthening of the signal.

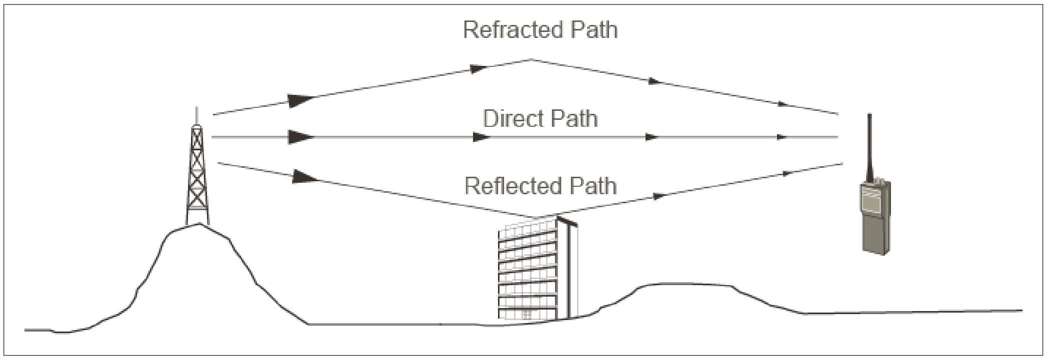


Figure 2-33: Radio Signal Paths

This effect can be understood more easily if one considers two radio signals appearing in the same place as sinusoids that are being added together (see Figure 2-34). If two signals arrive at the same time, their sinusoidal phases match; in this situation, the signals are called *in-phase*. When added together mathematically, this results in the same sinusoidal shape but with a greater magnitude.

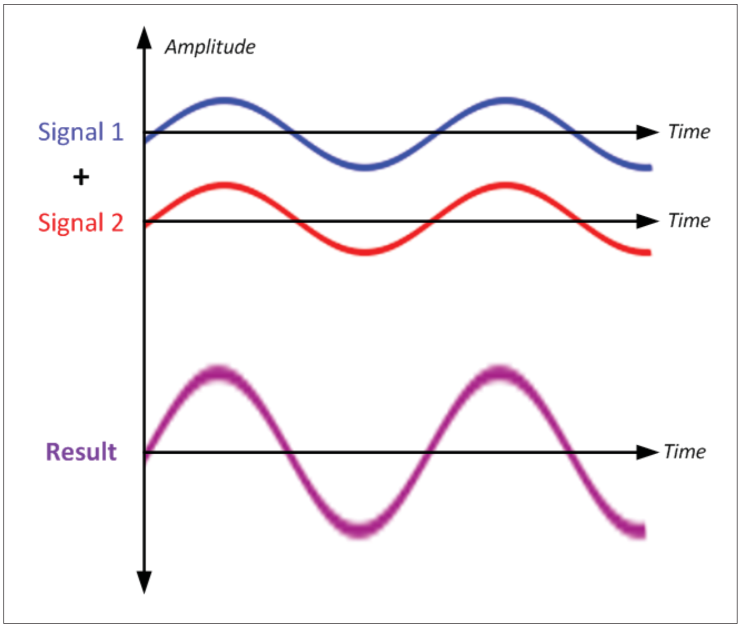


Figure 2-34: In-Phase Signals

If two signals arrive at different times, their sinusoidal phases differ and are said to be *out-of-phase* (see Figure 2-35). When added together mathematically, the result can range from a distorted or diminished signal to complete cancellation (180° out-of-phase).

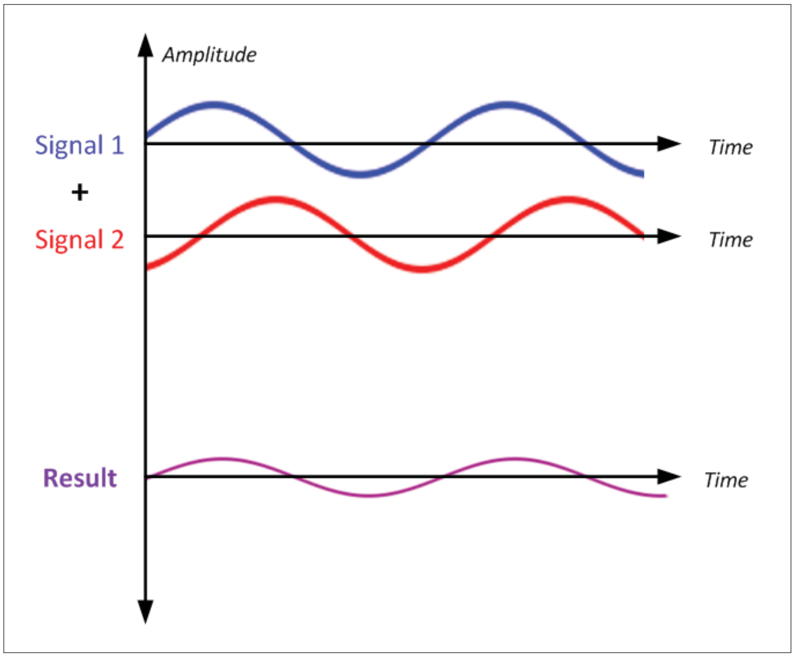


Figure 2-35: Out-of-Phase Signals

Equipment Placement, Terrain and Power

Just like a person's voice, as a radio signal travels through the air, it loses intensity due to absorption loss and attenuation—which is the reduction in power density the further it is from its source (think of a light getting dimmer the further away you are). Eventually, if enough total loss occurs, the receiver cannot distinguish the signal. All of the losses that cause a signal to lose intensity are collectively known as *path loss*.

Terrain can also have a profound effect on how a radio signal travels to its intended destination. Ideally, the receiver and transmitter would be in line-of-site with each other without any obstructions in between; in reality however, the space in between a transmitter and receiver is often filled with buildings or mountains that block signals, or shiny surfaces such as leaves, water or windows that reflect and refract them.

The quality of the air can be considered an invisible part of the terrain, as the amount of moisture in the air affects how much of the signal is absorbed. At a great enough distance the curvature of the Earth itself becomes an insurmountable factor in terms of terrain.

The challenge of distance, terrain and frequency effects in a radio communications link are often solved by a combination of the following:

- Increasing the power of the transmitted signal to overcome path loss and accommodate for technical limitations of the receiver
- Re-positioning of the radio equipment, particularly the antennas of the transmitter and receiver to convenient locations, for example, raising the antennas higher to overcome obstacles in the terrain

Sometimes line-of-sight communications are impossible because the terrain is simply too diverse, or the technical / regulatory limitations don't allow for increases in power or the use of convenient frequencies. Thankfully, there are creative ways to get around this problem. For example, when the curvature of the Earth itself becomes a physical obstacle at large distances, one can use HF frequency sky-wave communication to refract signals off of the Earth's atmosphere to reach receivers that are beyond the line-of-sight of the transmitter. In a later section of this manual, we will also explore how the arrangement or addition of more / various types of radio equipment can be used to create multiple radio links that overcome obstacles that would be insurmountable for a single link.

The challenge in designing a radio communication link can therefore be summarized as ensuring that the signal radiated (or directed) at the receiver is high enough in power and positioned adequately to account for:

- total path loss at the given frequency and terrain
- technical limitations of the receiver (see the "Reception" section).

RECEPTION

After the radio signal travels through the air, it reaches its intended destination, the *receiver*, which is a piece of electronic equipment that converts the RF signal back into an audio (or other intelligible) signal, so the signal can be interpreted by the listener (a person or computer). In essence, the receiver simply does the reverse of what a transmitter does.

A receiver's performance is defined by how well it can discern the intended radio signals from all other RF signals and noise in the air. Receiver performance characteristics fall into three categories:

1. **Sensitivity**: How small / weak the intended signal can be before the receiver is no longer able to discern it. Sensitivity characteristics of a receiver are often defined by seeing how strong the intended signal must be compared to the noise in the system while still remaining intelligible.
2. **Selectivity**: How well the receiver can discern the intended signal from other unwanted signals that differ in frequency.
3. **Fidelity**: How well the receiver can reproduce the original audio (or other intelligible) signal.

There are many different types and variations on receiver design. While not the simplest, the most commonly used for both AM and FM / PM is the superheterodyne design which has superior selectivity and sensitivity characteristics.

Although receivers are often complex electronic devices with many different variations on design, their operation can be summarized by six basic functional stages that are found in most devices:

1. Antenna
2. RF Filtering and Amplification
3. Tuning and IF Conversion
4. Demodulation
5. Information Signal Conditioning (AF Amplification or Data Processing)
6. Output

The block diagram below outlines these stages (see Figure 2-36).

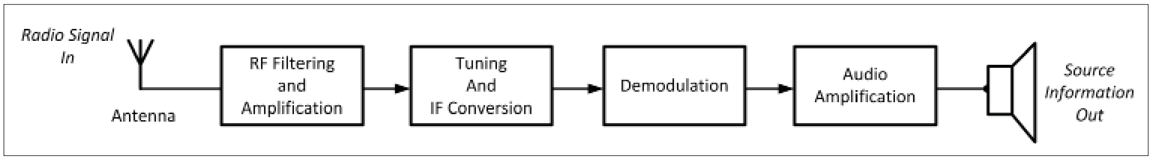


Figure 2-36: Receiver Operations

The elements of the receiver are detailed further in following sections.

Antenna

The antenna that is found on the receiver is often very similar (if not completely the same) to the antenna on the transmitter; that is, it is a piece of conductive material with dimension and orientation characteristics chosen to suit the radio frequency of interest. When the antenna is in the presence of an EM field consisting of radio signals falling within the correct range of frequencies, the signal induces an electric current within the antenna that varies in time and amplitude with the radio signal. This current travels through the cable connecting the antenna to the receiver.

RF Filtering and Amplification

Often (but not always), the first set of electrical components the received RF signal will pass through with be a *Front End (RF) filter*.

RF Filters

An RF filter is an important piece of radio equipment that consists of electrical components such as resistors, inductors and capacitors that are configured to resonate at a certain range of frequencies. That is, the impedance characteristics become optimal when the correct range of frequencies is applied. Signals with frequencies that fall within the range of resonant frequencies are either *passed* or *rejected* depending on the type of filter and what it is used for. Any frequencies that fall outside of this range are rejected or passed conversely.

Resonance at the desired frequencies is achieved by varying the values of the electrical components; this is known as *tuning* the filter circuit. RF filters range in size from small integrated circuits to extremely large external equipment, depending on the application.

The Front End filter is generally an internal circuit within the receiver and is configured to pass a range of resonant frequencies and reject everything else; this type of filter is known as a *Bandpass filter*. The range of frequencies that the filter resonates with is therefore known as the *passband* and all received electrical signals having frequencies that fall within this range are *passed* onto the next part of the receiver.

Note that the passband for a Front End filter is generally quite wide and additional filtering is required to block all of the undesired signals. This filtering is done to exclude any unwanted signals that may at the very least interfere and/or distort with the information that is intended for the listener and, at worst, damage the receiver itself. How well the filter can pass the desired signal and reject undesired signals has a great effect on the selectivity and sensitivity performance of the receiver.
The bandwidth of the pass band of the filter is defined between the points where the amplitude of the signal is decreased by 3 db.

The diagram (see Figure 2-37) shows what a bandpass filter's output would look like in the frequency domain if one were to input a signal of uniform amplitude, but "sweeping" incremental frequency (this is known as a **frequency response**).

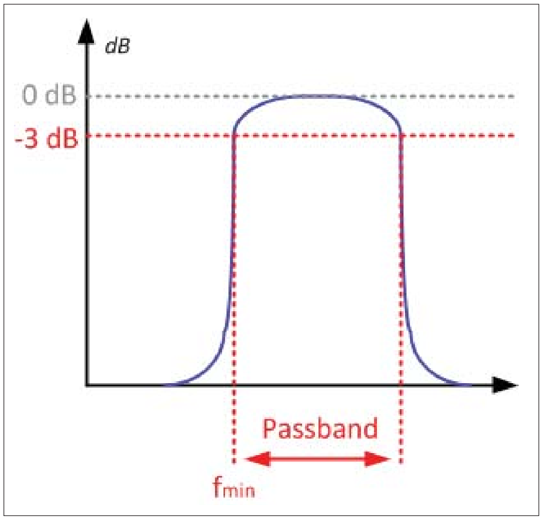


Figure 2-37: Bandpass Filtering

In other applications, filters can be designed to suit other particular frequency rejection requirements:

- **Band Reject**: The opposite of a bandpass, where all frequencies are passed except for a selected range (see Figure 2-38)

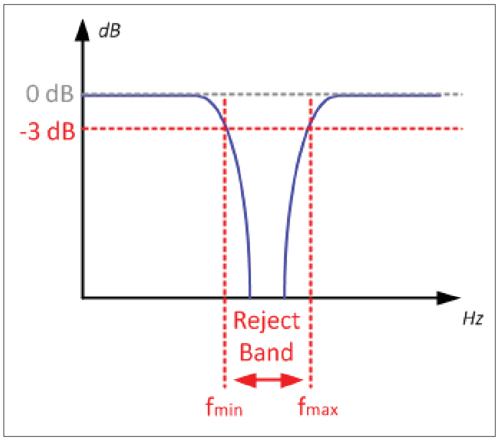


Figure 2-38: Band Reject Filters

- **Low Pass**: All signals above a defined frequency are rejected, while frequencies below this point (down to 0 Hz) are passed; this point is known as the *cutoff frequency* (See Figure 2-39)

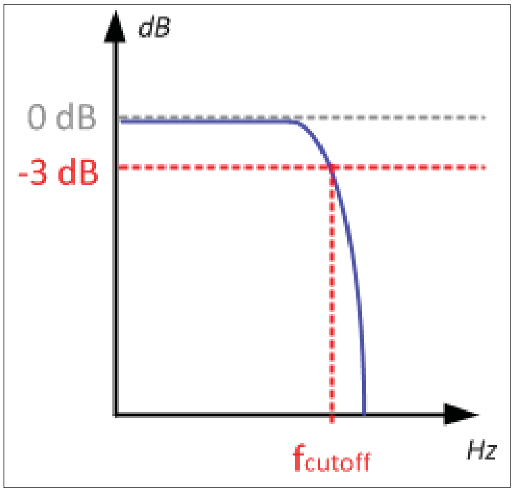


Figure 2-39: Low Pass Filters

- **High Pass**: All signals below a defined cutoff frequency are rejected (see Figure 2-40)

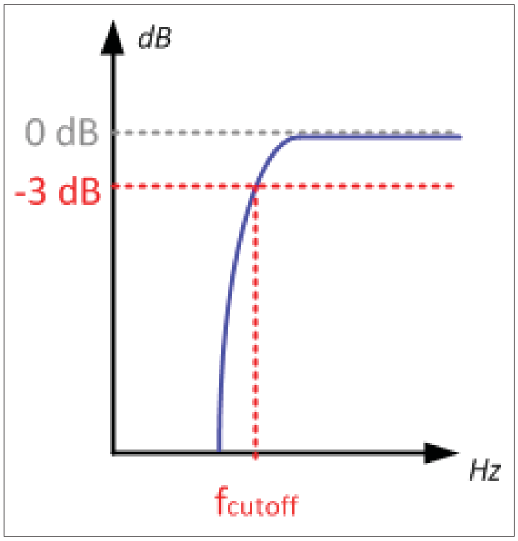


Figure 2-40: High Pass Filters

Filters are usually comprised of a number of electronic elements, but the following generalized symbols are used to represent a filter in functional diagrams (see Figure 2-41).

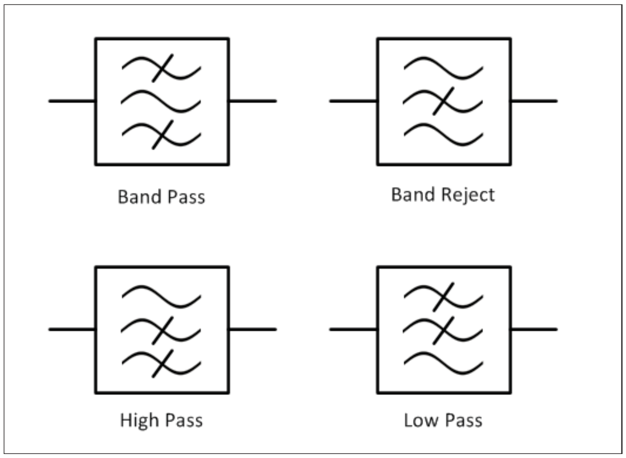


Figure 2-41: Schematic Symbols for Filters

RF Amplifier in the Receiver

By the time a radio signal is received by the receiver, it is likely very low in power and therefore must be amplified to a usable level; for this an RF amplifier is used. The amplifier will operate similarly to RF amplifier found in the transmitter, but at much lower power, since the signal does not need to be transmitted over large distances.

In addition to increasing the signal strength of the received signal, the amplifier performs additional filtering by only amplifying signals within a narrow frequency range, thus eliminating some of the undesired signals that may have passed through the Front End filter.

Tuning and IF Conversion

Next, the received, amplified and filtered received RF signal (which still contains the desired information) is usually converted to an *Intermediate Frequency (IF)* signal; this is done to facilitate exact selection of the desired RF frequency while allowing most of the radio electronics to remain fixed in value and operation, even if the desired reception frequency is changed.

The IF frequency itself is usually a fixed frequency that is common in all devices regardless of manufacturer, but dependent on application and receiver operation. Standard IF frequencies for FM radios, for example, include 21.4 MHz or 455 MHz.

The RF signal is frequency mixed with a *Local Oscillator (LO)* signal to produce the IF signal. Since this process is mathematical, only a specific RF frequency and specific LO frequency will produce the required IF frequency. The LO frequency is therefore varied, thereby allowing the user to select which exact RF frequency is received. This varying of the LO to select the desired RF frequency is called *tuning*.

Sometimes there is more than one IF conversion in a receiver, each progressively lower in frequency. This is done for various reasons, but chiefly because lower frequencies are easier and cheaper to work with on an electronics level. The IF signal is usually amplified as well, once again to make it easier to work with in the demodulation stage that follows.

Demodulation

Although the received signal is now been converted to a lower frequency signal in the IF stage, the signal still consists of two components: the higher IF frequency carrier signal and the information signal that we wish to extract. The detection circuits in a receiver perform the opposite function of the modulation process in the transmitter; they remove the IF frequency leaving only the information signal through a process called *demodulation*.

The exact nature of the demodulation process varies depending on the type of modulation the receiver is designed to work with. In AM, for example, the demodulation process involves keeping the envelope shape signal and removing the high frequency components. Alternately in FM (and PM), the changes in frequency are converted to a low frequency information signal. In either case, the high frequency components are removed leaving only the original information signal.

In a receiver that is used for a digital radio application, the demodulation process detects the digital modulation to produce a stream of bits that are processed into an intelligible form of information in the final stage of the reception process.

Information Signal Output

The only thing that remains is to output the information signal to the user to complete the process of radio communication.

In an analog audio application, the AF signal is amplified to the desired level and output through a speaker, headphones or other. Like the microphone but reversed in operation, the speaker is simply a device that converts electrical voltages to vibrations in the air that can be heard by a person. If pre-emphasis was applied to the audio prior to transmission, the reverse process, known as *de-emphasis*, is performed prior to output as audio.

In a digital application, the bitstream is processed by computing circuitry to produce some sort of useable output, such as audio, visual information on a screen or control information for other electronic devices to use.

Squelch

If one listens to the audio coming from a receiver when there is no signal being transmitted, one will hear random noise (known as white noise) that is caused by various natural and man-made electromagnetic phenomenon in the air. Needless to say, listening to this noise the entire time that the receiver is on is undesirable, but a receiver must remain on in order to “listen” for any transmissions that may occur.

A squelch circuit solves this problem by muting the audio that comes out of the radio until a carrier signal of sufficient strength is detected. This means that the user is spared listening to noise, but the receiver can still “listen” for a signal and the audio circuits activate when there is something to listen to. The action of the audio being turned off is commonly referred to as *squelching* or closing of the squelch circuit.

Unsquelching is the opposite operation; it is when audible reception is enabled at the presence of a sufficiently strong signal (or *control signal*, as will be shown in a later section). The action of the audio being turned off is commonly referred to as unsquelching or opening of the squelch circuit.

Unsquelching is usually set to occur at a higher signal level than the signal at which the squelch closes; this avoids the audio rapidly turning on and off. The difference between the squelch opening and closing points is known as the *squelch window* (see Figure 2-42).

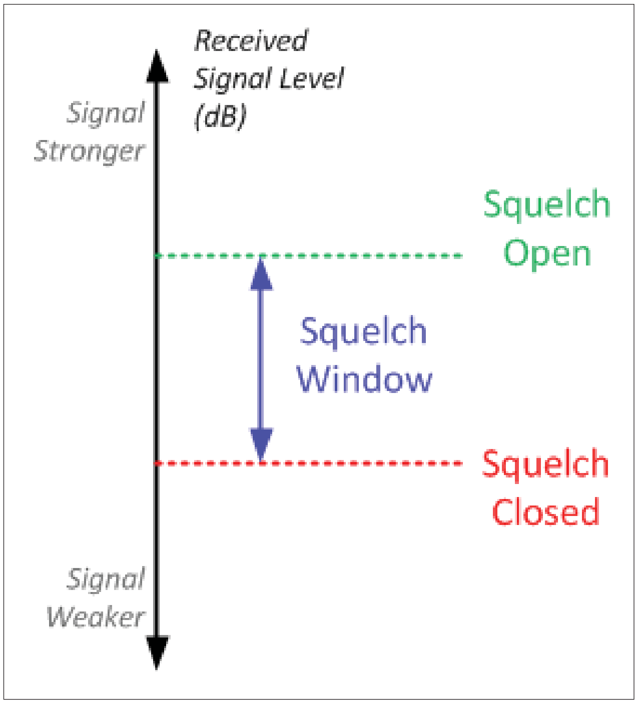
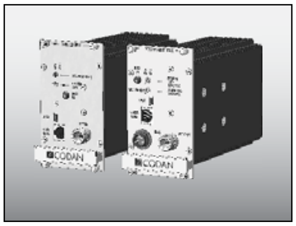


Figure 2-42: Squelch Operations



CHAPTER 3: RADIO SYSTEMS

RECEIVERS AND TRANSMITTERS IN A SYSTEM

Up to this point we have examined the basic elements of a radio communications system and how they interact in the simplest arrangement: a single piece of equipment that transmits a signal, and a single piece of equipment that receives a signal. It has been established that this arrangement is susceptible to interference, is limited in its range and is heavily impacted by the terrain in which it is established.

At this point, it is convenient to think of the receiver and transmitter to be the “building blocks” of a radio communications system, which can be added and arranged to provide required functionality and to overcome the previously mentioned limitations that are again summarized below:

- Equipment placement limitations
  - Distance between receiver and transmitter
  - Blocking / interfering terrain
  - Antenna height / space requirements
- Equipment technical (and/or regulatory) limitations
  - Transmission power
  - Receiver sensitivity
- Frequency availability / allocations

Radio System Terminology

The words used in radio communications can become cumbersome when describing receiver and transmitter operation in a radio system with many elements. This is particularly evident when one tries to plan a radio communications system graphically. To solve this, simplified terms and symbols are used to replace lengthier words and terms. Some key examples of this are listed below:

- A receiver or the act of signal reception is often shortened to '**RX**'
- A transmitter or the act of transmitting a signal is often shortened to '**TX**'
- Frequency is often shortened to the lowercase letter 'f', with the descriptor of the frequency stated in subscript afterward.
  For example:
  - In a system that uses a single receive frequency of 150 MHz, this can be stated as:

    $$f_{RX} = 150.000\text{MHz}$$

  - In a system that uses a single transmit frequency of 150.5 MHz, this can be stated as:

    $$f_{TX} = 150.500\text{MHz}$$

  - In a system that uses multiple frequencies (e.g., 150 MHz, 150.5 MHz, 151 MHz) for receiving or transmitting, these can be stated as:

    $$f_1 = 150.000\text{MHz}$$
    $$f_2 = 150.500\text{MHz}$$
    $$f_3 = 151.000\text{MHz}$$
    $$\dots$$

  Note that in this case, the direction (i.e., whether the frequency is being used to receive or transmit) would be shown graphically or stated otherwise.

System Diagrams

System diagrams are helpful in understanding how a radio system with multiple links works and are useful tools to use when planning a radio system. These may range in complexity from a simple block diagram listing equipment and frequencies, to a geographically accurate map indicating coverage, detailed equipment information and more. A top-down view diagram as shown below is the simplest form of planning diagram (see Figure 3-1).

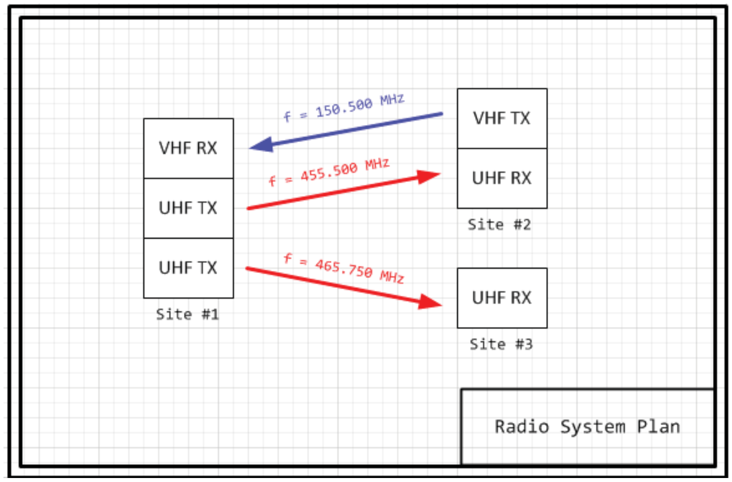


Figure 3-1: Communications Plan

Another type of planning tool that is often used is called a *link budget*. This diagram (see Figure 3-2) outlines all of the losses and gains for a single link—from the source to the receiver for the purpose of mathematically adding all of the gains and subtracting all of the losses (in decibels), to estimate if the signal that is to reach the recipient is strong enough.

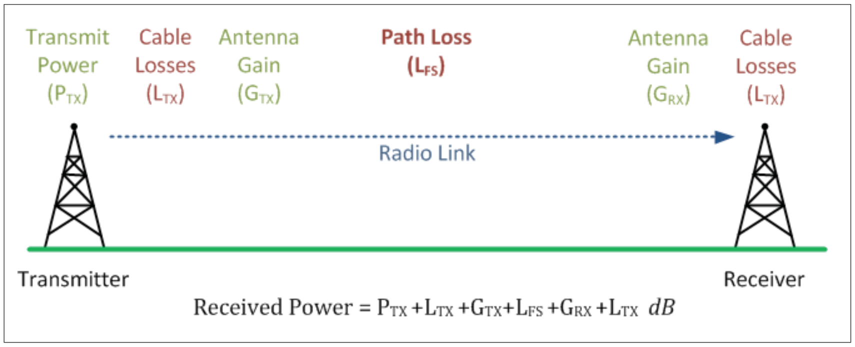


Figure 3-2: Link Budget Diagram

Topographic and path profile maps can be used to add further detail on how coverage will be affected by terrain in a system plan (see Figure 3-3).

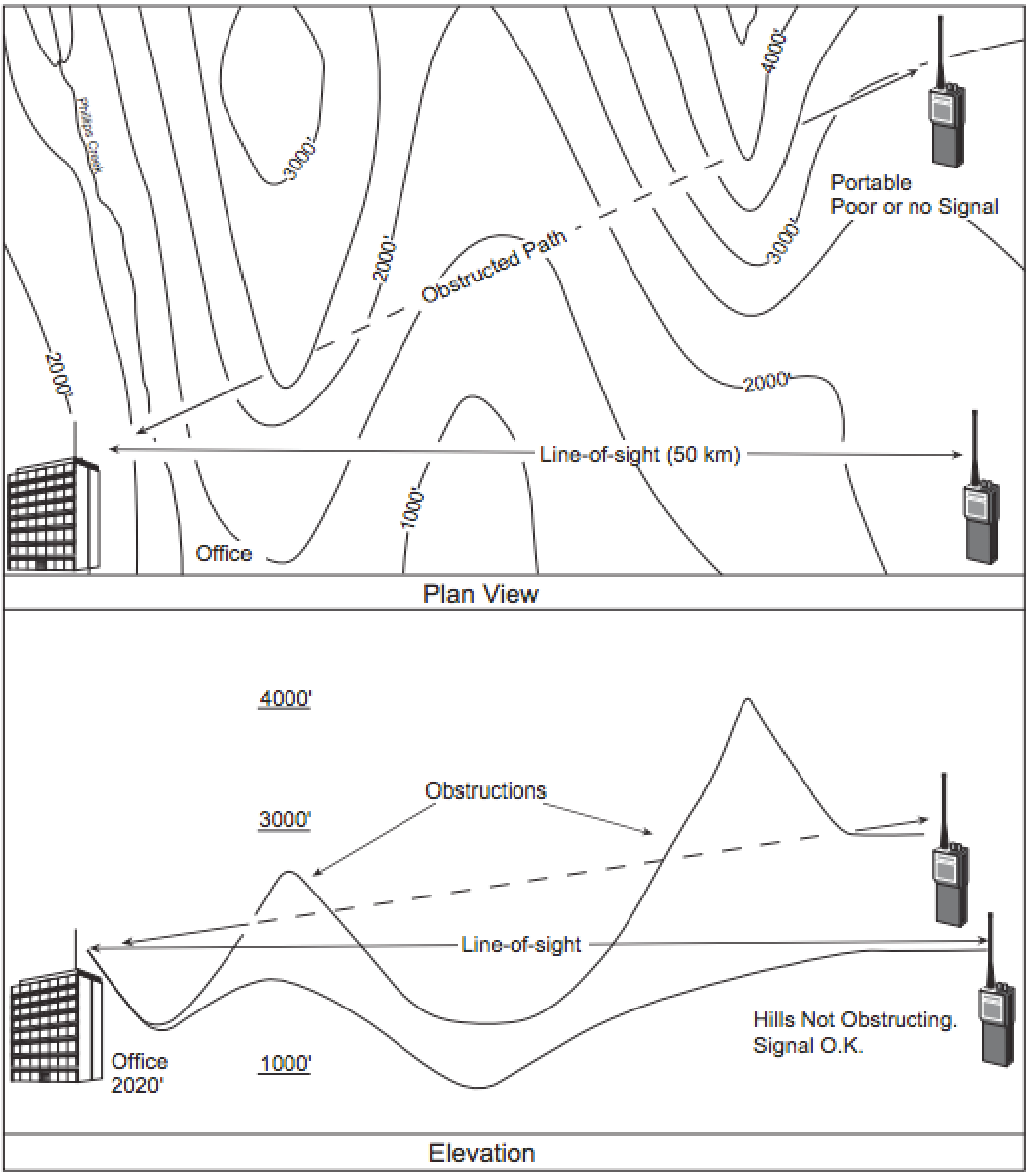


Figure 3-3: Examples of Topographic Design Maps

TRANSCEIVERS AND EQUIPMENT CO-LOCATION

In looking at the simple radio arrangement of a transmitter and a receiver, one might ask "what if the person at the receiver needs to communicate back to the person at the transmitter"? In this scenario, it is convenient to have a single piece of radio communication equipment that can perform both receiving and transmitting functions, so that the two users in the arrangement can easily switch roles from transmitter to receiver. See Figure 3-4.

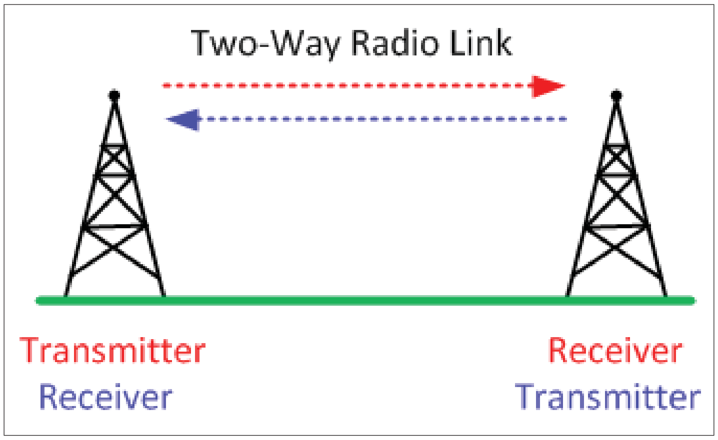


Figure 3-4: Two-Way Linking

A single piece of radio communications equipment that can both receive and transmit is known as a *transceiver* (see Figure 3-5).

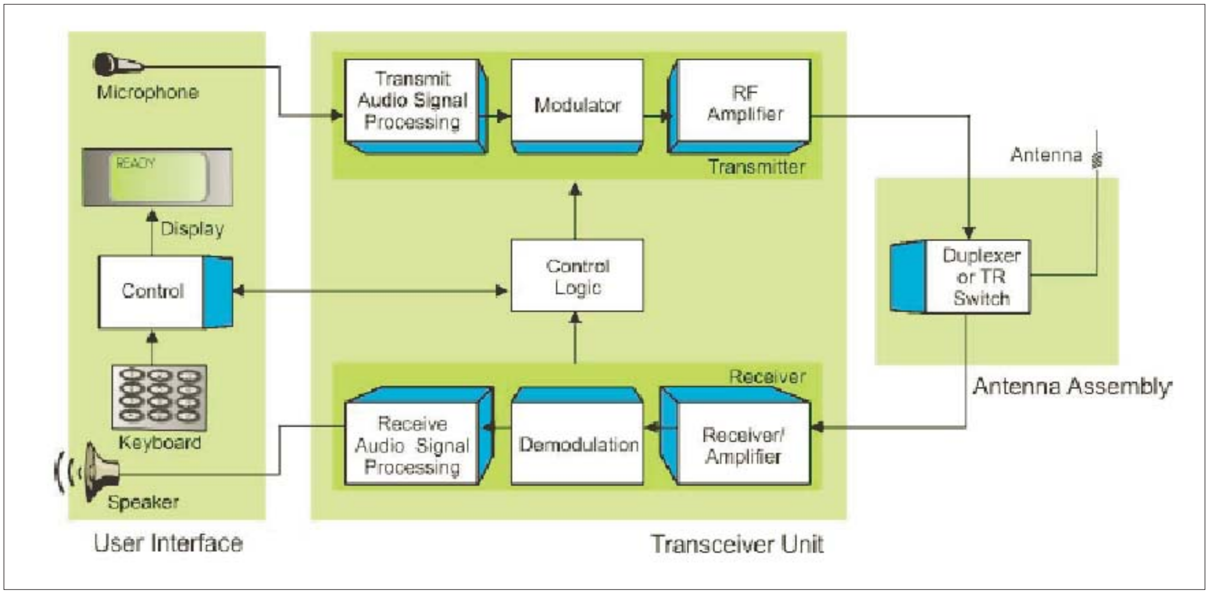


Figure 3-5: Transceiver Equipment

While combining the receiver and transmitter in a single unit is convenient, it does pose some technical challenges. Positioning a transmitter directly beside a receiver poses a risk of too much radio energy going into the receiver and damaging the equipment; this can be thought of the radio equivalent to putting a loudspeaker right next to someone's ear. There are a few ways to deal with this issue that can be used separately or in combination:

- Separate the receiver and transmitter sufficiently in frequency – ideally this separation must be large, such as operating in two different bands altogether
- Add a filter to the input of the receiver to block out the operating frequency of the transmitter
- Separate the transmit and receive antennas by a large vertical distance

This last point is most often not possible because of special restrictions and because quite often transceivers only have one antenna that both the receiver and transmitter share. This latter case is desirable because of savings on materials and space, however the sharing of an antenna between a receiver and a transmitter poses a technical challenge that must be addressed using additional equipment, such an antenna relay or a duplexer.

Antenna Relay

When transmission and reception is not required to be simultaneous, an electrically activated switch known as an *antenna relay* can switch the input of the antenna to the transmitter when the transceiver is transmitting; otherwise the antenna is connected to the receiver (see Figure 3-6).

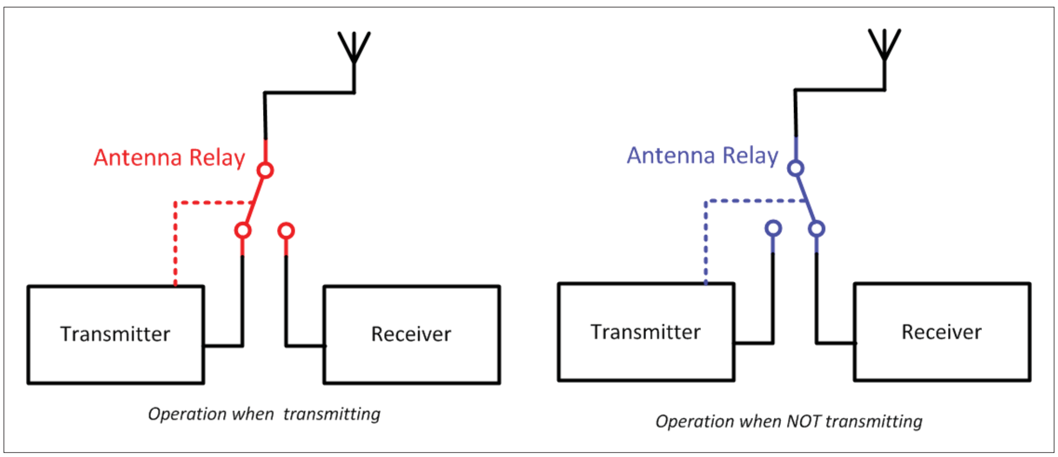


Figure 3-6: Shared Antenna Relay

Duplexers

A *duplexer* is a piece of equipment that allows a receiver and transmitter to share a single antenna. Unlike an antenna relay, which only allows either the receiver or transmitter to use the antenna at any given time, a duplexer allows both devices to operate simultaneously using the same antenna provided that the receive and transmit frequency are sufficiently different.

Duplexers are large external RF filters that are designed to reject / block the transmitter frequencies at the receiver input, but pass all of the other frequencies, particularly those to which the receiver is tuned to receive.

The diagram below (see Figure 3-7) shows the frequency response of a duplexer; that is how it responds to a signal of constant amplitude that is swept across all frequencies of interest. Note that at the tuned frequency, any signal with that frequency is blocked.

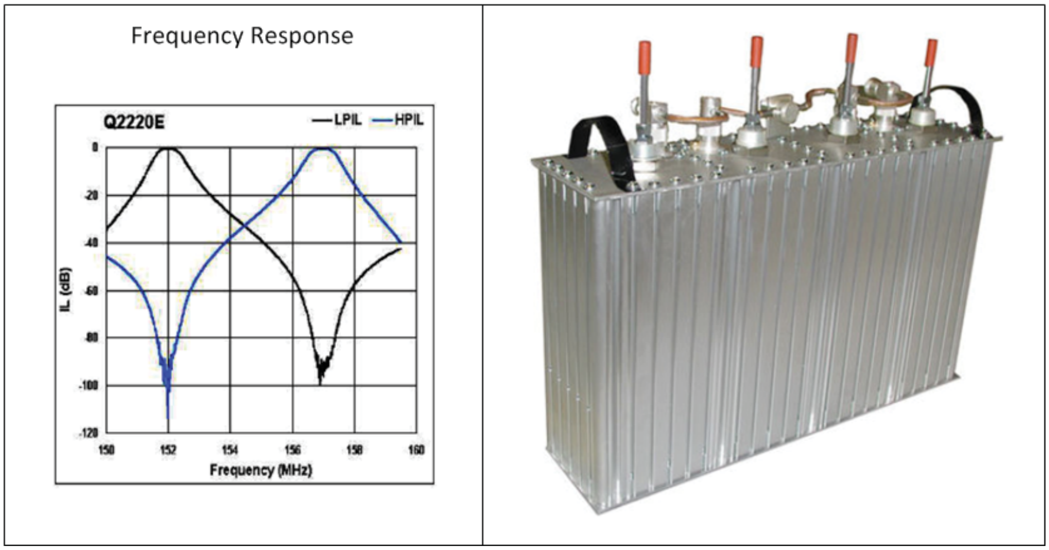


Figure 3-7: Example – Duplexer and Frequency Response

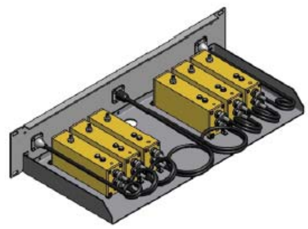
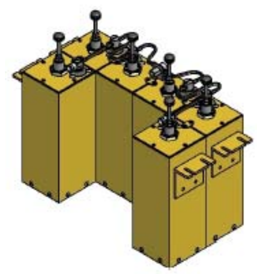
Selecting a duplexer for a radio application is a careful balance of the following six elements:

1. **Frequency Band / Frequency Range**: the range of frequencies that the duplexer can operate in. Note that the duplexer is tuned to specific receive and transmit frequencies within this band.
2. **Frequency Separation**: the difference in frequency between the receiver and transmitter measured in Hertz.
3. **Power Requirement**: the maximum amount of RF power that will be transmitted into the duplexer measured in Watts.
4. **Insertion Loss**: the amount of power that will be lost from the output of the transmitter to the output of the duplexer measured in decibels.
5. **Isolation**: the amount the receiver input is isolated from the transmitter output measured in decibels.
6. **Physical Space Allowance**: the size of the duplexer unit and how it fits within the physical constraints of the installation.

All of these elements are interconnected and having a strict requirement for one element will most likely mean a compromise for another element. For example, the physical size (and cost) of the duplexer can increase greatly with more stringent separation, power and frequency band requirements; and one must be careful to allow enough room to accommodate the equipment.

The table below shows an example of how much size can increase when one or more of the elements (in this case power requirement, insertion loss and isolation) are varied due to requirements. See Table 7.

Table 7: Duplexer Size Comparison

	Duplexer 'A'	**Duplexer 'B'**
		
Band:	T-Band	T-Band
Frequency Range:	470-512 MHz	470-512 MHz
Maximum Power:	100W	350W
Minimum TX/RX Separation:	3 MHz	3 MHz
Insertion Loss:	1.8 dB	1.6 dB
Isolation:	75 dB	85 dB
Height:	3.5 inches	8 inches
Width:	19 inches	19 inches
Depth:	8.84 inches	15 inches

*Images Courtesy of Comprod

Duplexers must be carefully tuned before use and care must be taken not to physically alter the duplexers configuration once its set. For example, large duplexers have 'plunger' type adjustments that must be carefully positioned for correct operation. Unfortunately, these adjustments are often bumped and mishandled after a radio system has been installed, potentially causing improper operation and damage.

MODES OF COMMUNICATION

We have established that radio equipment can transmit, receive or perform an alternating or simultaneous combination of both. These equipment capabilities define how pieces of equipment interact with one another in a radio system. To understand this better, one can think of system elements in terms of mode of communication.

Unfortunately, the terminology used in describing communication modes is often confusing, because the same terms are used to describe different aspects of a radio (and general electronic) communications system. This confusion is also increased due to varying usage between different individuals and organizations. Two aspects that are often referred to in terms of mode are equipment operation and channel direction.

Equipment Mode

Equipment operation can be categorized in terms of reception and transmission capabilities using the following four mode types:

1. RX/TX Only
2. Simplex
3. Half Duplex (or ‘Two-Frequency Simplex’)
4. Full Duplex (or simply ‘Duplex’)

The commonly used definitions outlined below (see Table 8) apply to the characterization of radio communications **equipment**.

Table 8: Radio Communications Equipment Definitions

	RX/TX Only	Simplex	Half Duplex	Full Duplex
Operation	Can perform receive or transmit function only	Can perform either receive or transmit functions, but not simultaneously	Can perform either receive or transmit functions, but not simultaneously	Can perform both receive or transmit functions simultaneously
Frequency	Single operating frequency per channel	Single operating frequency per channel – the receive and transmit functions share a single frequency	Different operating frequencies for receive and transmit functions	Different operating frequencies for receive and transmit functions
Antenna	Single antenna	Single antenna switched via an antenna relay, or separate receive and transmit antennas	Single antenna switched via an antenna relay or shared via duplexer, or separate receive and transmit antennas	Single antenna shared via a duplexer, or separate receive and transmit antennas

Channel Mode

Channels of communication can also be categorized by mode (see Table 9). There are three possible types when describing a link between two stations:

1. Simplex
2. Half Duplex
3. Full Duplex (or simply ‘Duplex’)

Table 9: Radio Communications Channels Definitions

	Simplex	Half Duplex	Duplex
Communication Direction	Uni-directional; receive or transmit, but not both	Bi-directional – receive and transmit, but not at the same time	Bi-directional – receive and transmit simultaneously

MULTIPLE USERS AND CHANNEL ACCESS TECHNOLOGIES

Adding more radio equipment and more users to a radio system naturally increases its complexity, so when planning a radio system beyond the simple single-RX-single-TX arrangement, methods for managing system usage must be employed.

Frequency Division Multiple Access

Frequency Division Multiple Access (FDMA) is the most fundamental concept in radio communications when dealing with multiple users in a system. The frequency allocation is divided into channels, which are then assigned to particular users or for particular functions. The figure below (see Figure 3-8) shows how a frequency band can be divided into two communication channels using *frequency division multiplexing (FDM)*.

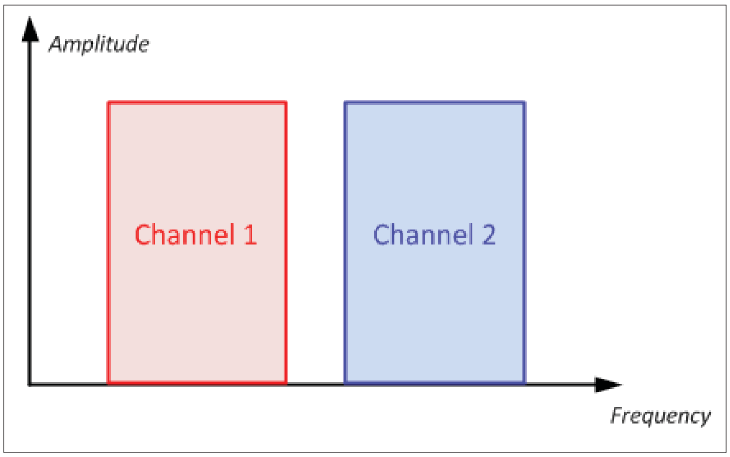


Figure 3-8: FDMA Concept

When a device is communicating on a FDM system using a frequency carrier signal, its carrier channel is completely occupied by the transmission of the device. For some FDM systems, after it has stopped transmitting, other transceivers may be assigned to that carrier channel frequency. When this process of assigning channels is organized, it is called frequency division multiple access. Transceivers in an FDM system typically have the ability to tune to several different carrier channel frequencies.

FDMA is a clean concept and can be the only organization scheme required for multiple users when establishing a system in an area that has a small amount of users. However, in areas where frequency allocations are not easily available and/or the number of users is high (in densely populate areas, for example), the usage of available frequencies must be optimized.

Two fundamental solutions to this problem exist:

1. **Narrowbanding**: Decrease the bandwidth that radio equipment requires to operate, thus allowing for smaller channels.
2. **Channel Access / Sharing Technologies**: Apply techniques and add technology to radio equipment that allows multiple users to access the same channels without interfering with one another.

Selective Calling

Selective calling is the simplest type of channel sharing. It allows users to ignore all transmissions on a channel that not intended for them or their group of users. This is accomplished in analog systems by adding *Continuous Tone Squelch System (CTCSS)* subtones—sometimes called PL tones—to transmissions and having receiving equipment capable of tone squelch operation. Equivalent processes are found in digital communications, but use various digital codes rather than tones.

A particular CTCSS tone is assigned to a user or group of users; only transmissions on the channel that contain the assigned CTCSS tone will cause the corresponding user's radio to un-squelch. The tone is always present, however, as it is a *subtone* (not audible and filtered out by the radio equipment). The CTCSS tone can be thought of as a key; only transmitting users that have the correct key can "open" another user's receiver.

It should be noted that transmissions that occur at the same time on the channel will still interfere with each other, even if they are members of different groups and are assigned different CTCSS tones. As such, selective calling serves more to reduce the nuisance of receiving unwanted transmissions, rather than providing more efficient use of a channel.

Time Division Multiple Access

Time Division Multiple Access (TDMA) is a more advanced type of channel sharing that allows users to share a single radio channel with greater efficiency. In TDMA, a channel is divided into time slots that are then allocated to each user; the user can then only use the channel during their designated time slot.

When a user communicates on a TDMA system, they are assigned a specific time position on the radio channel; this user then can only use the channel within the designated times. By allowing several users to use different time slots on a single radio channel, TDMA systems increase their ability to serve multiple users with a limited number of radio channels.

The figure below shows how a single carrier channel is time-divided into two communication channels (see Figure 3-9).

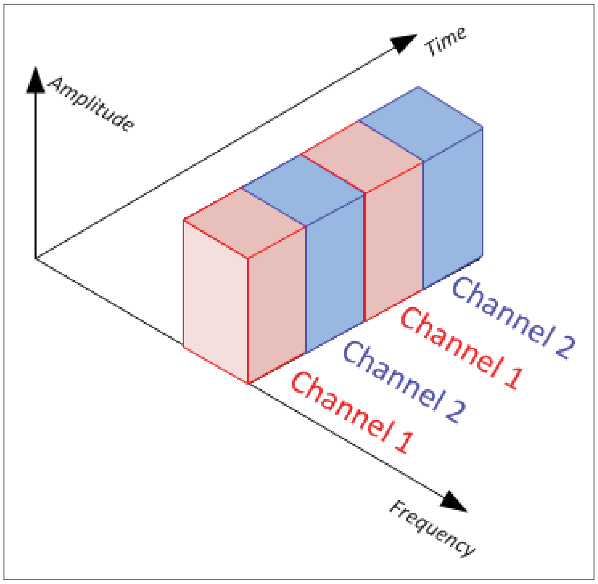


Figure 3-9: Time-Divided Channel

RADIO SYSTEM EQUIPMENT CATEGORIES

When thinking of radio communications on a system level, it is useful to make a further distinction between the equipment used to directly interface with a user and the equipment that the user does not directly interface with but is used to support communications:

- Interface equipment
- Radio Infrastructure equipment
- Back-end Infrastructure equipment

Interface Equipment

Interface equipment is any electronic equipment that is interfaced with directly by the user to communicate into a radio system or directly to another user; this can be a microphone, a computer or a complete radio in itself.

In the latter case, the sending and receiving interface equipment communicate directly, no additional infrastructure is needed (e.g., two people speaking on 'walkie-talkies').

Radio Infrastructure

Radio infrastructure consists of radio equipment that is used to enhance coverage capabilities of a radio system to extend coverage, overcome physical obstacles, include a greater number of users and more. Infrastructure is logically positioned between the sending and receiving interface equipment.

Infrastructure typically consists of *radio stations* that serve as interface points into a system and/or interaction points within a system. Infrastructure can generally be considered to be larger in size and higher in power than interface radio equipment.

When in use, a radio infrastructure is considered a fixed and/or permanent point within the radio communications system; it should be noted, however, that transportable infrastructure is available that can be moved and deployed as necessary to establish a radio communications system where one does not permanently exist.

When speaking of LMR systems, radio infrastructure is further divided into two categories:

1. **Conventional**: Communication management (e.g., call routing, channel allocation, channel selection) is a manual / user-determined process.
2. **Trunked**: Communication management is an automated process.

Backhaul Infrastructure

Some more complex radio communications systems employ *Backhaul infrastructure* to interconnect radio equipment using a different form of electronic communications technology such as telephony or IP (internet) connections.

INTERFACE EQUIPMENT

Radio interface equipment takes many forms, from pagers to mobile phones to commercial radio equipment. For the sake of this text, we will focus on the most common types used in LMR.

Portables

Portable Handsets (or simply '*Portables*', or sometimes '*Subscribers*' depending on network configuration) are small handheld radio transceivers that can communicate into infrastructure or directly to other portables. They are generally ruggedized for heavy use, are battery operated and have a relatively low power transmitting capability (see Figure 3-10).

Figure 3-10: Portable

Mobiles

Mobile units (or 'Mobiles') are similar in operation to handsets, but are usually mounted inside a vehicle; for this reason they are generally larger in size and have higher transmit power capabilities (See Figure 3-11).

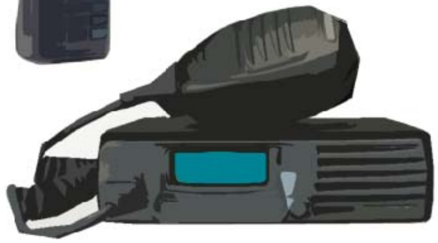


Figure 3-11: Mobile

Consoles

Consoles are interface points that not only communicate, but also control the operation of infrastructure equipment and are thus used to manage communications within a system. These range in form and complexity, from a terminal that looks like a stationary telephone, to a full computer setup with monitors and headsets. Consoles differ in many respects to mobiles and portables, particularly in that the latter are used in the field as transportable communications devices and consoles are generally at a fixed location (see Figure 3-12).

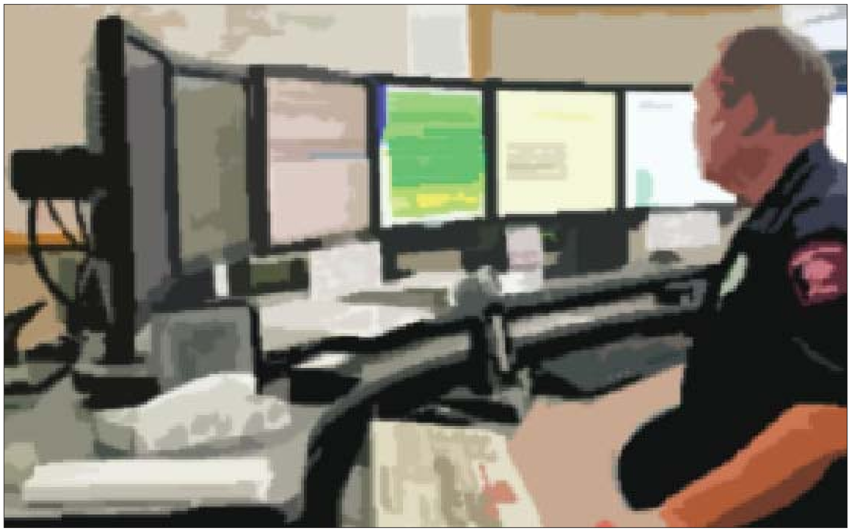


Figure 3-12: Consoles

CONVENTIONAL RADIO INFRASTRUCTURE

Conventional infrastructure describes any geographically fixed radio system in which the users of the system directly manage communication traffic within the system. Fundamentally, this means allocating channels to users, which are then manually selected by the users when they need to be used. While there is some limited channel selection and signal routing tools available on conventional systems, they are relatively basic when compared to the automated functions of Trunked infrastructure (see the next section). Since conventional systems are relatively simple, they still comprise the majority of radio systems used today.

Base Stations

A *base station* is a radio station that serves as an infrastructure access point into a radio communications system. It can provide a two-way communications point with other infrastructure or interface equipment, or can provide a one-way broadcast communications to multiple receiving users (see Figure 3-13).

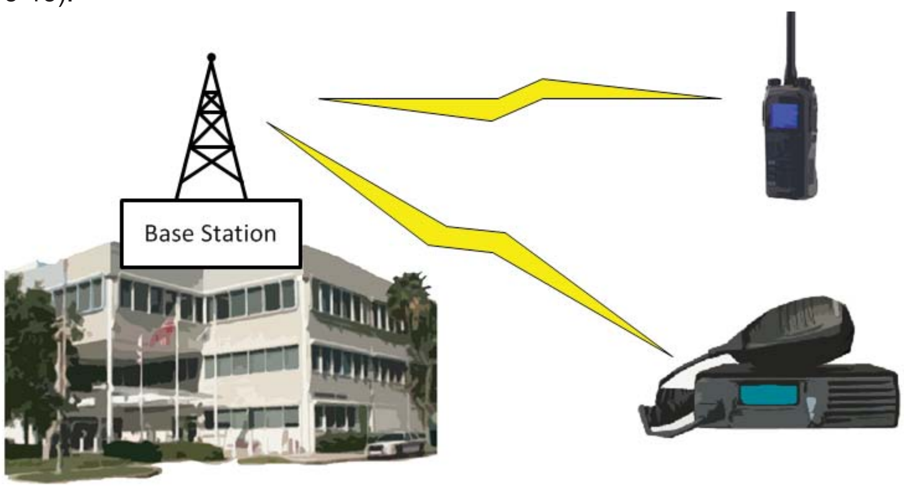


Figure 3-13: Base Station Setup

Base stations typically operate in simplex mode, either transmitting or receiving, but not both simultaneously.

The base station is connected to the interface equipment and will allow the user to communicate via the infrastructure network to other users. The interface equipment is often collocated with the base station (a handheld microphone connected right to the radio, for example), however, this is not always the case. Sometimes it is more convenient to have the large, high-power equipment located remotely, which is known as a *remote base station* configuration (see Figure 3-14).

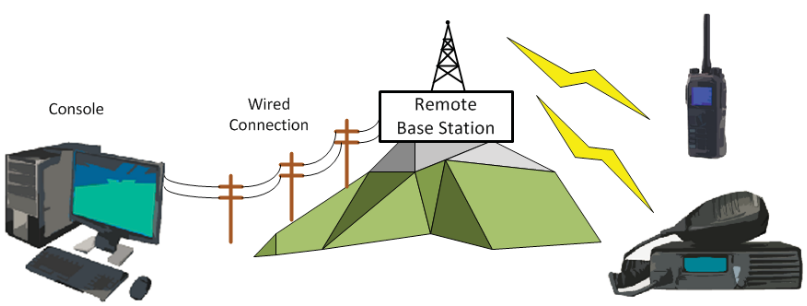


Figure 3-14: Remote Base Station Setup

In this remote base station configuration, one of the following technologies must be used to connect the user's interface equipment to the base station infrastructure equipment.

E&M

E&M (which stands for either Ear and Mouth, or Earth and Magnet)) is the first and most basic form of remote control for a base station. E&M provides a set of protocols for using a two-wire / telephone connection (an "E" lead and an "M" lead) to send audio signals and a *Push-To-Talk (PTT)* signal that tells the transmitter to start transmitting the input audio signal. Alternately, E&M protocols can also use a microwave link, which is another separate RF channel that uses a different set of technologies and frequencies.

There are five different E&M interface types or models named Type I, II, III, IV, and V. Each type has a different wiring arrangement, hence a different approach to transmit E&M supervision signaling (on-hook / off-hook signaling). The signaling side sends its on-hook/off-hook signal over the E-lead. The trunking side sends the on-hook / off-hook over the M-lead.

Tone Remote

A tone remote base station also employs a wired or microwave link, but rather than just simple audio and PTT functions used in E&M, a tone remote has more advanced capability. A remote console may be located in the same building as the transmitter, or they may be separated by many miles and use telephone lines or microwave links to connect the transmitter with the tone remote console.

Control signals and voice are sent from the tone remote console, over the dedicated pathway, to the transmitter. It is necessary to install a tone remote adapter to the transmitter to convert the tone remote signals to actual channel and Push-to-Talk (PTT) functions. Standard Tone Remote Frequencies are shown in Table 10.

Table 10: Standard Tone Remote Frequencies and Levels

Standard Tone Remote Frequencies	Relative Levels	Tone Duration
High Level 2175 Hz Guard Tone	10 dBm	120 ms
1950 Hz Transmit F1 Function	0 dBm	40 ms
1850 Hz Transmit F2 Function	0 dBm	40 ms
2050 Hz CTCSS Monitor Function	0 dBm	40 ms
Low Level Guard Tone	-20 dBm	20 ms
Voice Peaks	0 to 5 dBm	

Figure 3-15 shows a Tone Remote Control sequence the host will send to control the base station.

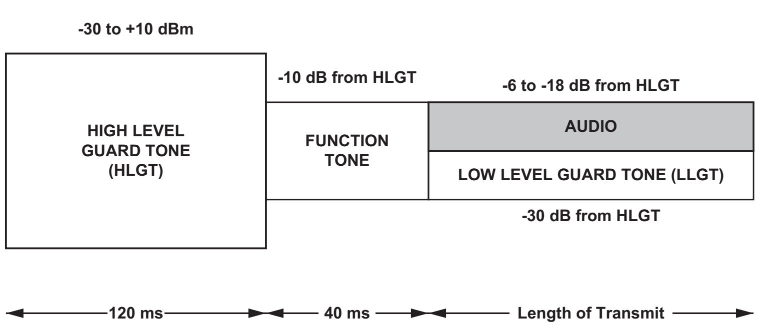


Figure 3-15: Tone Remote Control Sequence

Note that there may be multiple tones used at a time, for example, if one wishes that a radio function be performed while the transmitter is transmitting (that is, PTT is enabled by a tone). There are two different ways this case is handled, depending on the manufacturer of the tone remote equipment:

1. **Single Tone Format**: Function Tones are sent as a separate item from the PTT signal. A Function Tone is sent at 0 dBm for 350 msec. While a PTT signal is sent at -10 dBm for the entire time the voice is being transmitted.
2. **Sequential Tone Format**: In this method, a guard tone of 2175 is sent at +10 dBm for 40 msec, followed by a function tone at 0dbm for 40 msec, which is then followed by a continuous PTT tone of 2175 at -20 for the entire duration of the voice transmission.

IP Control

The fast growth of internet communications has allowed for rapid expansion of IP controlled remote base stations; this is often called *Radio-Over-IP (RoIP)*. This solution requires the infrastructure equipment to be fitted with a device that connects via an IP network connection such as Ethernet, to a console interface with the required control software.

This method of remote base station control not only circumvents the high costs of leasing telephone lines, but also allows for expanded features and functionality, such as monitoring levels, alarming, logging communications, integration with other technologies such as cellular communications and others. While the disadvantages are few, network security and reliability must be seriously considered in these applications.

Repeaters

A repeater is as an intermediate radio station that re-transmits the signal it receives (see Figure 3-16). Repeaters are used when simple transmitter-to-receiver communications are not possible, for example:

- When the transmitter is too limited in transmitting power to reach the intended receiver(s)
- When too great a distance separates the transmitter and receiver(s)
- If a permanent obstacle between the transmitter and receiver prevents a path for communication
- If the frequencies used by the transmitter do not match or are not permitted in the area of where the receivers are located

Repeaters typically operate in duplex mode, as the instantly relay whatever is being received.

Note that repeaters can be configured to connect to other repeaters creating a network that can span a potentially large distance and overcome various physical obstructions.

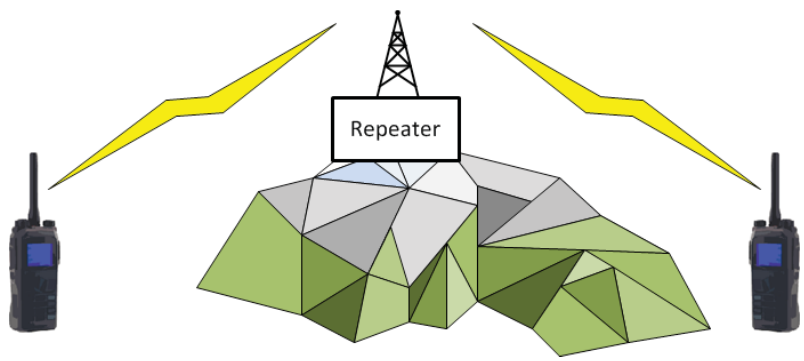


Figure 3-16: Repeater Setup

Voting

Voting is a more advanced configuration that is used to overcome challenges of reception coverage in radio system infrastructure.

Voting involves using multiple receiver stations to maintain optimal reception from portable / mobile users that are transmitting from various locations in a given area. As a portable / mobile user moves in the area, their line of sight to the infrastructure receiver can become blocked by terrain such as mountains or buildings. When his happens, any transmissions the user may try to send from their mobile / portable may not reach the receiver, or if they do, the signal may be noisy. This is a particular problem when the coverage area is large and geographically diverse.

A voting configuration solves this problem by having receiver stations deployed at various locations over the area so that there is reception coverage everywhere that it may be needed. These receivers all have a backhaul (i.e., IP, wire or radio) connection to a central device known as a *voting controller*.

When a transmission from the user occurs, the voting controller ‘listens’ to the demodulated audio from each of receivers in the system and determines which one has the strongest signal. It does this by measuring the amount of noise in the audio using statistical methods to calculate a signal’s *Signal -to-Noise ratio (S/N)* or alternately the *Received Signal Strength Index (RSSI)* for analog communications, or *Bit Error Rate (BER)* for digital communications.

Once the voting controller picks (i.e., votes for) the best received signal, it passes this signal onto the intended location via a backhaul connection or radio re-transmission.

To better understand the concept of voting, imagine the following scenario involving a car equipped with a mobile radio traveling down a highway surrounded by mountains (see Figure 3-17).

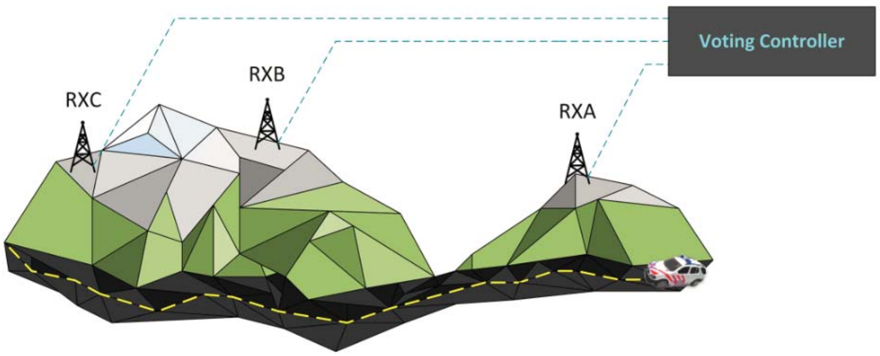


Figure 3-17: Example – No Voting Process

When the driver of the car is driving near the beginning of the highway and tries to transmit, the signal is strongly picked up by the nearby receiver A, more poorly by the distant receiver B and hardly at all by the obscured receiver C (see Figure 65). In this case, the voting controller chooses to ignore the audio received by receivers B and C, since the signal from receiver A has the least amount of noise and is therefore the strongest.

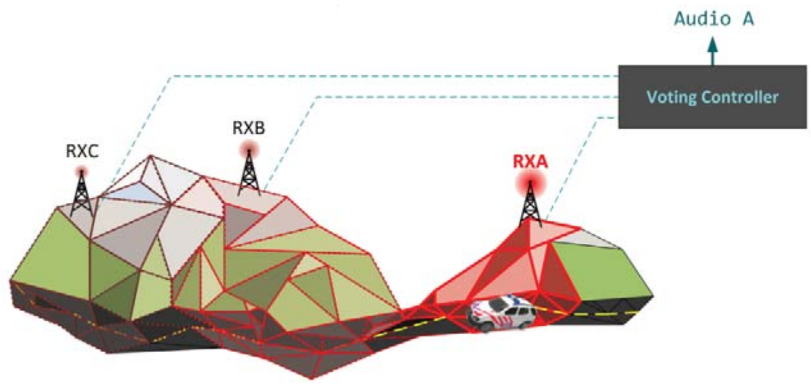


Figure 3-18: Voting Controller – Chooses RXA

As the car moves down the highway, the signal at receiver B becomes stronger, thus the voting controller ignores the audio from receivers A and C (see Figure 66).

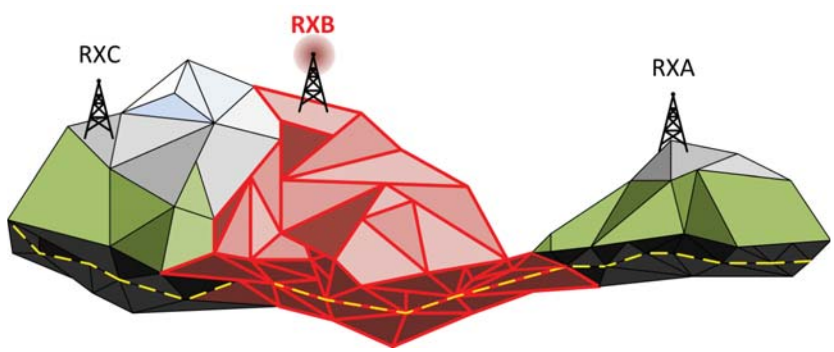


Figure 3-19: Voting Controller – Chooses RXB

When the receiver is not receiving any intelligible signal, it produces a continuous *Status Tone* over the backhaul line to the controller; this allows the controller to exclude receivers that are not receiving a signal at all from the voting process.

Simulcast

Simulcast is a more advanced configuration that is used to overcome challenges of transmission coverage in radio system infrastructure while improving frequency efficiency (see Figure 3-20).

Simulcast systems use multiple transmitter stations using the same transmitting frequency to provide a more complete range of coverage rather than a single centrally located transmitter (Broadcast) or multiple transmitters using multiple frequencies (known as Multicast). Like in a voting system, the communication is managed by central control equipment that routes the audio signals to the transmitter sites via backhaul connections.

In theory, all of the stations transmit or re-transmit the same signal on the same frequency simultaneously. Since the transmitting frequency is the same at each station, a single channel can be used to receive the signal, regardless of which coverage area the mobile / handheld receiver finds itself in—meaning that the user does not have to change channels and frequency allocation requirements are kept to a minimum.

While this seems like a simple concept, the technical challenges involved in a Simulcast system can be great, because when the same signal is transmitted from multiple points there will likely be areas of overlap where a signal from multiple transmitters will be received at once.

Recall that two signals received at a single point will add together; if they are in-phase the addition will make the signal stronger, if they are out-of-phase, the signal will be diminished or distorted. Since the transmitters vary in distance to a receiver finding itself in this overlap area, the signals will arrive at different times causing destructive interference. If one signal is much stronger than the others, this isn't much of a problem because the receiver can inherently discern the stronger signal (known as capture effect), however if one or more signals are similar in strength this is a significant problem.

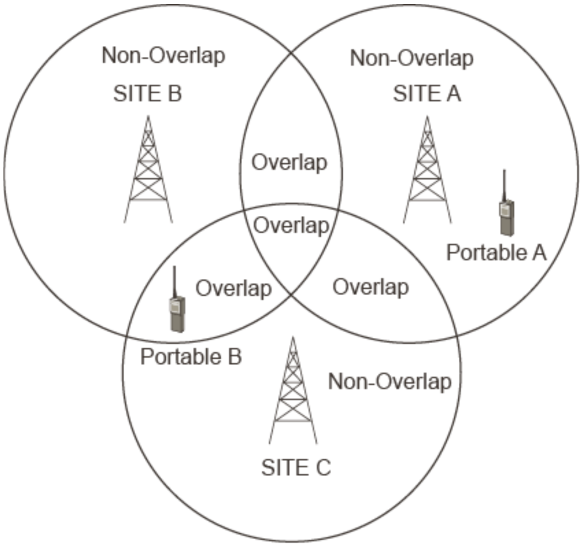


Figure 3-20: Site Transmission Coverage

Additionally, if the frequencies of all of the stations are not exactly the same (or as close as possible), other detrimental interference can occur in overlap areas.

Given these technical challenges, there are a number of solutions that must be employed in a Simulcast system for communications to work correctly:

- Site placement and design
- Audio phase delay and amplitude equalization
- RF frequency stabilization

Site Placement and Transmitter Characteristics

The easiest way to avoid the problems that arise when areas of transmission overlap is to design the radio system such that coverage is maximized and overlap is minimized. Naturally this optimized scenario is difficult to achieve in practice, however transmitter placement and height can be varied to provide the best solution possible. Varying the output power of the transmitters can also provide some control over overlap areas, but this approach is constrained by equipment and regulatory limitations on power and its effectiveness is a point of contention among experts.

Audio Phase Delay and Time Synchronization

Introducing a calculated time delay into the transmissions can ensure that interference is not destructive at points of interest / heavy use that fall into areas of overlap.

As an example, imagine a mobile receiver in a car needs to receive a signal on a highway that falls in the overlap area of two transmitters (see Figure 3-21). The signal from the nearest transmitter reaches the mobile first, so when the signal from the further transmitter reaches the mobile, it becomes a source of interference.

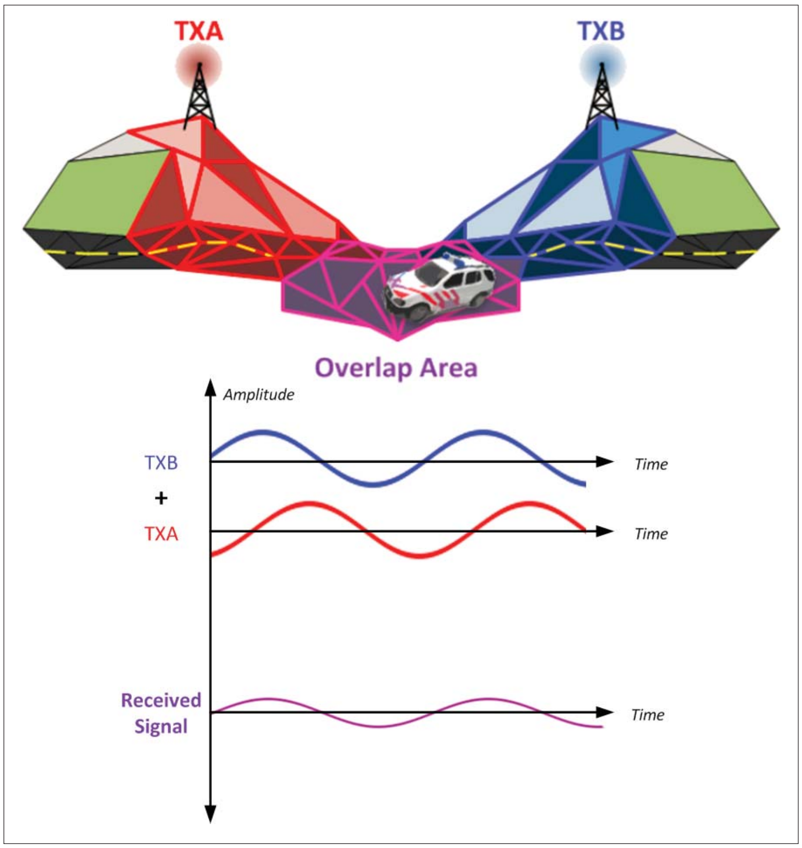


Figure 3-21: Example – Transmission Interference

To correct this, the time it takes the signal from the furthest transmitter is calculated and the signal from the nearest transmitter is delayed accordingly so that both signals arrive approximately at the same time (see Figure 3-22).

Since the phase of the signals is the same, they will add together in such a way that is not destructive because the audio that is captured by the receiver is the same regardless of which signal is received.

This solution, however, introduces a new problem in that the transmitter stations need to be very carefully synchronized in time so that one transmitter may be delayed relative to another. This is achieved by the addition of precise timing equipment to each transmitter station. Often, this is a *GPS receiver* that receives a very high-accuracy timing signal produced and transmitted by *Geosynchronous Positioning System (GPS)* satellites that orbit the Earth.

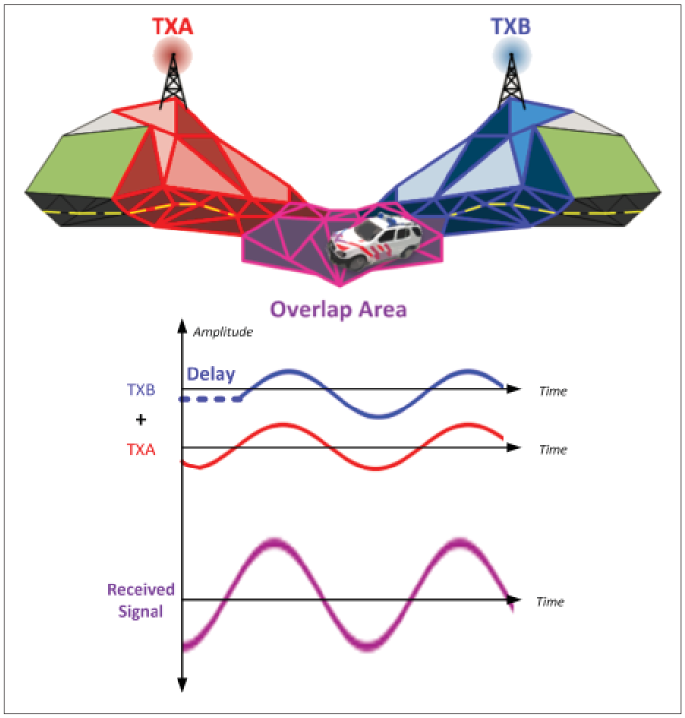


Figure 3-22: Example – Audio Phase Delay

Note that the process of adding delay often requires expensive equipment and substantial engineering, such as field testing or computerized delay spread calculations, to gauge exactly how long it takes for a transmission from a particular station to reach a given point.

Interference can further be controlled by varying the amplitude of the input audio signal on each of the transmitting stations; in doing this, the received signal is uniform regardless of which station it is received from.

RF Frequency Stabilization

When multiple signals are apparent in the overlap area, destructive interference between RF signals will occur when the signals do not match in frequency due to phase misalignment. The result is an audible “buzz” that can affect the quality of received audio from simply being annoying to the point of incoherence.

This is mitigated by using transmitter equipment that has a very high frequency stability specification, or by adding equipment that eternally controls or disciplines the transmitter oscillator to produce a very stable frequency. Once again, a GPS receiver is used to discipline the oscillators in the transmitter equipment to a high-accuracy reference signal.

When to Use Simulcast

Simulcast is often used in conjunction with voting infrastructure technology to provide a full transmission and reception solution. Due to the challenges inherent in Simulcast systems, engineering and equipment costs tend to be considerably higher than in simpler configurations. The use of a Simulcast configuration should therefore only be planned when other, simpler configurations are not possible.

TRUNKED RADIO INFRASTRUCTURE

Trunked radio infrastructure is a more advanced geographically fixed radio system infrastructure that uses computer systems to automate the management of communication traffic within the radio system. While this approach is generally more expensive due to the need for advanced control equipment and increased engineering / commissioning complexity, there are significant advantages to the use of a trunked system over a conventional system:

- Provides a significant improvement in ease of use over conventional radio infrastructure since users don't have to manually select channels
- Allows for a large number of users to use limited frequency resources with greater efficiency due to the power of computerized channel management
- Enables advanced communication management by allowing communication to specific individual users or combinations/groups of users

Trunking Operation (Dedicated Control Channel)

In a trunked radio system application, mobiles and portables are called *subscribers*, since they are registered within the radio system and managed by the system controller. Subscribers are assigned to *talkgroups* (or simply groups) and each group has a number of channels that are shared among the subscribers. These user communication channels are called *traffic channels* (see Figure 3-23).

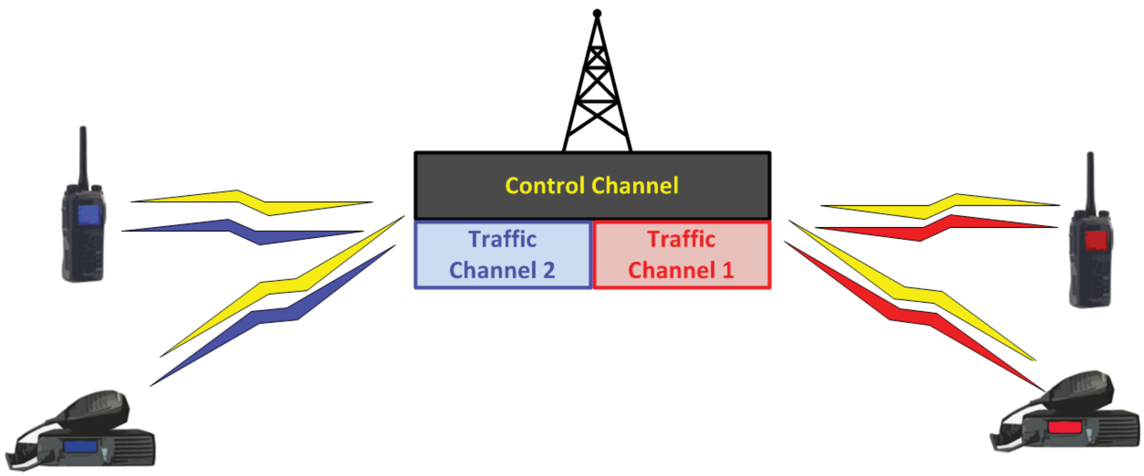


Figure 3-23: Trunked Radio System with Multiple Traffic Channels

There is also a specific channel known as the *control channel*, which is used by the system controller equipment to wirelessly send information and grant channel usage permission to the user's mobiles or portables. The information on the control channel operates in the background and is not audibly heard by user. The control channel is usually a dedicated channel (i.e., a reserved frequency), but in some cases where frequency availability is particularly scarce, the control channel switches to an available traffic channel. Some trunking technologies forgo having a control channel altogether and rely on subtones on traffic channels to perform subscriber control functions.

When a user wishes to make a call to another user or group of users, the user's subscriber automatically sends a request to the controller via the control channel. The control channel then grants the user's and recipient's subscribers access to a vacant traffic channel and a communications session, known as a call, is established.

All traffic goes through the controller station; the subscriber transmitter signal is received and then retransmitted to the designated users and/or groups. Once a subscriber or a group of subscribers is granted access to a traffic channel, they have exclusive access to the channel for the duration of their call. Note that this process is very fast and mostly transparent to the user. From the user's perspective, the PTT button on the subscriber is depressed and the call is simply initiated with little noticeable delay.

Trunking Configurations

As with conventional infrastructure, trunking infrastructure can be arranged into different configurations to deal with the challenges of terrain and frequency availability.

A *single-site trunking* configuration is the simplest type of trunking system, in which a centrally located controller station manages all traffic and control functions of subscribers within its coverage area.

A *multi-site trunking* configuration consist of two or more trunking controller stations with separate coverage areas, linked together via IP backhaul communications. Voting and/or Simulcast methodologies are sometimes applied to optimize reception and transmission coverage, respectively, however this comes at the cost of increased system complexity.

Trunking Format

While analog trunking was traditionally available, the functional requirements of trunked systems are more easily addressed in a digital radio system. Development of new standards and technologies, as well as reduction in cost of the latter, has meant that the majority of trunked system that are now implemented use digital radio.

DIGITAL RADIO

A person or organization wishing to establish a radio system using any of the conventional or trunked applications described above can do so using either analog radio equipment, digital radio equipment or a mixture of both. While it is tempting to use the latest and most advanced equipment, it is important to understand the strengths and weaknesses of both types of technology, thus allowing one to make an informed choice.

The Advantages of Digital Radio

The process of digitizing audio prior to transmitting it allows for some significant advantages over analog communications:

- **Reduction of Noise**: The process of digitizing an analog signal inherently removes noise from a signal that is to be transmitted. On the side of reception, error correction can be performed to restore bits that were “lost” in the transmission by way of statistical calculation.
- **Improved Bandwidth**: The sending of bits rather than complex analog signals can reduce the bandwidth required for effective communication.
- **Improved Security**: Analog signals can theoretically be received by anyone who knows which frequency to “listen” to. Digital signals, however, can be very effectively encrypted (or encoded), meaning that only a recipient who has the correct encryption key can listen to and understand the transmission; anyone else trying to listen in would only hear unintelligible noise.
- **Advanced Functionality**: In addition to sending the bits of digitized audio in a transmission, other digital information can be sent that provide useful information such as user identity, diagnostics and control functions.

The Disadvantages of Digital Radio

While digital radio affords some advantages, there are still a number of reasons why analog communications remain widely used:

- **Decreased Coverage**: Analog radios can receive relatively weak signals; though the audio that the user hears is noisy, it is often intelligible. Digital radio on the other hand requires received bits to produce intelligible sound; if too many bits are corrupted during the transmission, the processing equipment will simply not output any audio at all. As a result, areas where intelligible analog audio can be received are abruptly cut off in digital communications. Not only does this mean a decreased coverage area, but also means unnerving effects for users that do not have any audible indication that a signal is fading.
- **Audio Delay**: The conversion to and from analog signals and the processing required introduces a delay that some users may find annoying or inconvenient.
- **Higher Equipment Cost**: Although the cost of digital equipment has reduced in recent years, the technology is still more expensive than traditional analog radio.
- **Adherence to Various Standards**: Analog radio is a fundamental technology that can generally be accessed by equipment produced by any manufacturer. Digital radio, however, introduces an element of computing which requires operational protocols. While there are several standardized protocols (P25 Digital, TETRA or DMR, for example), a manufacturer’s equipment will generally adhere to only one of them, meaning it will not work with another manufacturer’s equipment that uses a different standard.

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