PREFACE

Volume 1 of this workbook is intended to help you become familiar with basic electricity and electronics. It is not a requirement that you fully understand 100 percent of its content; however this information is the foundation of the US&R Communications Specialist (COMS) duties and will not be formally presented at this level during the course.

Read and perform all activities, within the workbook prior to the class. The workbook may be used for "reference" throughout the course. This includes its use during the final 100 question exam, which includes 10 questions from this workbook.

ACKNOWLEDGEMENTS

This workbook was prepared with the help, advice, and assistance of personnel from many local, state, and federal agencies. Materials were drawn from previously published documents. Most of the workbook's content was extracted from the United States Navy Electricity and Electronics Training Series.

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USING THIS WORKBOOK

Time to Complete

This workbook will take approximately eight hours to complete. The workbook has to be completed prior to attending the Communications Specialist Course. You will also need to bring this workbook to class with you, because it will become part of the manual you will have compiled by the end of the course.

While working through the workbooks read the learning objectives. The learning objectives state what you should be able to do after studying the material and the final course test is based on these objectives.

Learning Checks

You will find learning checks in the form of questions or equations at the end of critical knowledge areas. These learning checks are designed to help you understand the material found in the text. Plus, answering the questions correctly helps you accomplish the objectives. The answer key to the learning checks can be found in the back of this workbook.

STUDENT EVALUATION OF TRAINING (FEEDBACK)

We value your suggestions, questions, and criticisms concerning this workbook. Please complete the workbook evaluation form found at the end. This form can be turned in when you attend the Communications Specialist Course.

IF YOU NEED HELP

If you have any questions concerning the technical content please contact the individual whose email address was provided in the workbook cover letter.

CHAPTER 1: MATTER, ENERGY, AND ELECTRICITY

Learning Objectives

Upon completing this chapter, you will be able to

- State, using the water analogy, how a difference of potential (a voltage or an electromotive force) can exist. Convert volts to microvolts, to millivolts, and to kilovolts;
- State the meanings of electron current, directed drift, and ampere, and indicate the direction that an electric current flows;
- State the relationship of current to voltage and convert amperes to milliamperes and microamperes; and
- State the definitions of and the terms and symbols for resistance and conductance, and how the temperature, contents, length and cross-sectional area of a conductor affect its resistance and conductance values.

Electrical Energy

In the field of physical science, work must be defined as the PRODUCT OF FORCE AND DISPLACEMENT. That is, the force applied to move an object and the distance the object is moved are the factors of work performed.

It is important to notice that no work is accomplished unless the force applied causes a change in the position of a stationary object, or a change in the velocity of a moving object. A worker may tire by pushing against a heavy wooden crate, but unless the crate moves, no work will be accomplished.

Energy

In our study of energy and work, we must define energy as THE ABILITY TO DO WORK. In order to perform any kind of work, energy must be expended (converted from one form to another). Energy supplies the required force, or power, whenever any work is accomplished.

One form of energy is that which is contained by an object in motion. When a hammer is set in motion in the direction of a nail, it possesses energy of motion. As the hammer strikes the nail, the energy of motion is converted into work as the nail is driven into the wood. The distance the nail is driven into the wood depends on the velocity of the hammer at the time it strikes the nail.

Energy contained by an object due to its motion is called KINETIC ENERGY. Assume that the hammer is suspended by a string in a position one meter above a nail. As a result of gravitational attraction, the hammer will experience a force pulling it downward. If the string is suddenly cut, the force of gravity will pull the hammer downward against the nail, driving it into the wood. While the hammer is suspended above the nail it has ability to do work because of its elevated position in the earth's gravitational field. Since energy is the ability to do work, the hammer contains energy.

Energy contained by an object due to its position is called POTENTIAL ENERGY. The amount of potential energy available is equal to the product of the force required to elevate the hammer and the height to which it is elevated.

Another example of potential energy is that contained in a tightly coiled spring. The amount of energy released when the spring unwinds depends on the amount of force required to wind the spring initially.

Electrical Charges

A field of force exists in the space surrounding any electrical charge. The strength of the field is directly dependent on the force of the charge.

The charge of one electron might be used as a unit of electrical charge, since charges are created by displacement of electrons; but the charge of one electron is so small that it is impractical to use. The practical unit adopted for measuring charges is the COULOMB, named after the scientist Charles Coulomb. One coulomb is equal to the charge of 6,280,000,000,000,000,000 (six quintillion two hundred and eighty quadrillion) or (6.28×10^{18}) electrons.

When a charge of one coulomb exists between two bodies, one unit of electrical potential energy exists, which is called the difference of potential between the two bodies. This is referred to as ELECTROMOTIVE FORCE, or VOLTAGE, and the unit of measure is the VOLT.

Electrical charges are created by the displacement of electrons, so that there exists an excess of electrons at one point, and a deficiency at another point. Consequently, a charge must always have either a negative or positive polarity. A body with an excess of electrons is considered to be negative, whereas a body with a deficiency of electrons is positive.

A difference of potential can exist between two points, or bodies, only if they have different charges. In other words, there is no difference in potential between two bodies if both have a deficiency of electrons to the same degree. If, however, one body is deficient of 6 coulombs (representing 6 volts), and the other is deficient by 12 coulombs (representing 12 volts), there is a difference of potential of 6 volts. The body with the greater deficiency is positive with respect to the other.

In most electrical circuits only the difference of potential between two points is of importance and the absolute potentials of the points are of little concern. Very often it is convenient to use one standard reference for all of the various potentials throughout a piece of equipment. For this reason, the potentials at various points in a circuit are generally measured with respect to the metal chassis on which all parts of the circuit are mounted. The chassis is considered to be at zero potential and all other potentials are either positive or negative with respect to the chassis. When used as the reference point, the chassis is said to be at GROUND POTENTIAL.

Occasionally, rather large values of voltage may be encountered, in which case the volt becomes too small a unit for convenience. In a situation of this nature, the kilovolt (kV), meaning 1,000 volts, is frequently used. As an example, 20,000 volts would be written as 20 kV. In other cases, the volt may be too large a unit, as when dealing with very small voltages. For this purpose the millivolt (mV), meaning one-thousandth of a volt, and the microvolt (μV), meaning one-millionth of a volt, are used. For example, 0.001 volt would be written as 1 mV, and 0.000025 volt would be written as 25 μV.

When a difference in potential exists between two charged bodies that are connected by a conductor, electrons will flow along the conductor. This flow is from the negatively charged body to the positively charged body, until the two charges are equalized and the potential difference no longer exists.

An analogy of this action is shown in the two water tanks connected by a pipe and valve in figure 1. At first the valve is closed and all the water is in tank A. Thus, the water pressure across the valve is at maximum. When the valve is opened, the water flows through the pipe from A to B until the water level becomes the same in both tanks. The water then stops flowing in the pipe, because there is no longer a difference in water pressure between the two tanks.

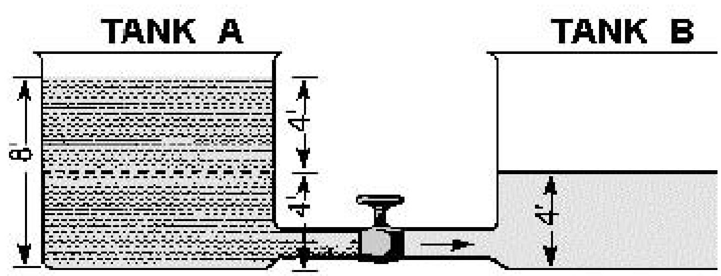

Figure 1.—Water analogy of electric differences of potential.

Electron movement through an electric circuit is directly proportional to the difference in potential or electromotive force (emf), across the circuit, just as the flow of water through the pipe in figure 1 is directly proportional to the difference in water level in the two tanks.

A fundamental law of electricity is that the ELECTRON FLOW IS DIRECTLY PROPORTIONAL TO THE APPLIED VOLTAGE. If the voltage is increased, the flow is increased. If the voltage is decreased, the flow is decreased.

☑**Learning Check**

1. What term describes voltage or emf?

2. Convert 2.1 kV to volts.

3. Express the following in more simple terms.

   a. 250,000 volts

   b. 25,000,000 microvolts

   c. millivolts

Electric Current

It has been proven that electrons (negative charges) move through a conductor in response to an electric field. ELECTRON CURRENT FLOW will be used throughout this explanation. Electron current is defined as the directed flow of electrons. The direction of electron movement is from a region of negative potential to a region of positive potential. Therefore electric current can be said to flow from negative to positive. The direction of current flow in a material is determined by the polarity of the applied voltage.

NOTE: In some electrical/electronic communities, the direction of current flow is recognized as being from positive to negative.

☑**Learning Check**

4. According to electron theory, an electric current flows from what potential to what potential?

Magnitude of Current Flow

Electric current has been defined as the directed movement of electrons. Directed drift, therefore, is current and the terms can be used interchangeably. The expression directed drift is particularly helpful in differentiating between the random and directed motion of electrons. However, CURRENT FLOW is the terminology most commonly used in indicating a directed movement of electrons.

The magnitude of current flow is directly related to the amount of energy that passes through a conductor as a result of the drift action. An increase in the number of energy carriers (the mobile electrons) or an increase in the energy of the existing mobile electrons would provide an increase in current flow. When an electric potential is impressed across a conductor, there is an increase in the velocity of the mobile electrons causing an increase in the energy of the carriers. There is also the generation of an increased number of electrons providing added carriers of energy. The additional number of free electrons is relatively small; hence the magnitude of current flow is primarily dependent on the velocity of the existing mobile electrons.

The magnitude of current flow is affected by the difference of potential in the following manner. Initially, mobile electrons are given additional energy because of the repelling and attracting electrostatic field. If the potential difference is increased, the electric field will be stronger, the amount of energy imparted to a mobile electron will be greater, and the current will be increased. If the potential difference is decreased, the strength of the field is reduced, the energy supplied to the electron is diminished, and the current is decreased.

☑**Learning Check**

5. What is the relationship of current to voltage in a circuit?

Measurement of Current

The magnitude of current is measured in AMPERES. A current of one ampere is said to flow when one coulomb of charge passes a point in one second. Remember, one coulomb is equal to the charge of 6.28 x 1018 electrons.

Frequently, the ampere is much too large a unit for measuring current. Therefore, the MILLIAMPERE (mA), one-thousandth of an ampere, or the MICROAMPERE (μA) ampere, is used. The device used to measure current is called an AMMETER and will be discussed in detail in a later module.

☑**Learning Check**

6. Convert 350 mA to amperes.

Electrical Resistance

It is known that the directed movement of electrons constitutes a current flow. It is also known that the electrons do not move freely through a conductor's crystalline structure. Some materials offer little opposition to current flow, while others greatly oppose current flow. This opposition to current flow is known as RESISTANCE, and the unit of measure is the OHM. The standard of measure for one ohm is the resistance provided at zero degrees Celsius by a column of mercury having a cross-sectional area of one square millimeter and a length of 106.3 centimeters. A conductor has one ohm of resistance when an applied potential of one volt produces a current of one ampere. The symbol used to represent the ohm is Ω.

Resistance, although an electrical property, is determined by the physical structure of a material. The resistance of a material is governed by many of the same factors that control current flow. Therefore, in a subsequent discussion, the factors that affect current flow will be used to assist in the explanation of the factors affecting resistance.

☑**Learning Check**

7. What is the symbol for ohm?

EFFECT OF CROSS-SECTIONAL AREA—Cross-sectional area greatly affects the magnitude of resistance. If the cross-sectional area of a conductor is increased, greater quantities of electrons are available for movement through the conductor. Therefore, a larger current will flow for a given amount of applied voltage. An increase in current indicates that when the cross-sectional area of a conductor is increased, the resistance must have decreased. If the cross-sectional area of a conductor is decreased, the number of available electrons decreases and, for a given applied voltage, the current through the conductor decreases. A decrease in current flow indicates that when the cross-sectional area of a conductor is decreased, the resistance must have increased. Thus, the RESISTANCE OF A CONDUCTOR IS INVERSELY PROPORTIONAL TO ITS CROSS-SECTIONAL AREA.

The diameter of conductors used in electronics is often only a fraction of an inch; therefore, the diameter is expressed in mils (thousandths of an inch). It is also standard practice to assign the unit circular mil to the cross-sectional area of the conductor. The circular mil is found by squaring the diameter when the diameter is expressed in mils. Thus, if the diameter is 35 mils (0.035 inch), the circular mil area is equal to (35) 2 or 1225 circular mils. A comparison between a square mil and a circular mil is illustrated in figure 2.

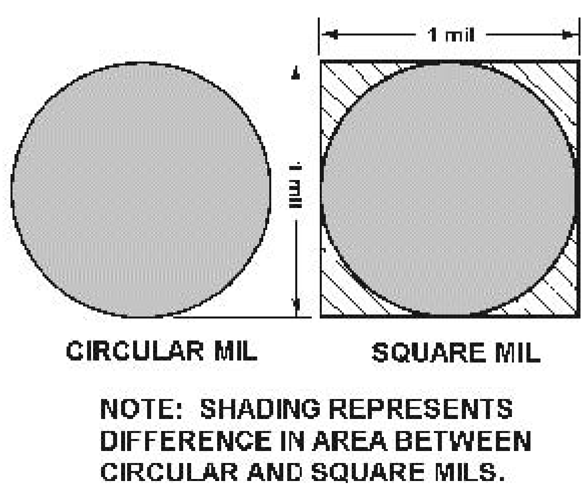

Figure 2.—Square and circular mils.

EFFECT OF CONDUCTOR LENGTH—the length of a conductor is also a factor which determines the resistance of a conductor. If the length of a conductor is increased, the amount of energy given up increases. As free electrons move from atom to atom some energy is given off as heat. The longer a conductor is, the more energy is lost to heat. The additional energy loss subtracts from the energy being transferred through the conductor, resulting in a decrease in current flow for a given applied voltage. A decrease in current flow indicates an increase in resistance, since voltage was held constant. Therefore, if the length of a conductor is increased, the resistance increases. **The resistance of a conductor is directly proportional to its length.**

☑Learning Check

8. Which wire has the least resistance?

   a. Wire A-copper, 1000 circular mils, 6 inches long.

   b. Wire B-copper, 2000 circular mils, 11 inches long

Electrical Resistors

Resistance is a property of every electrical component. At times, its effects will be undesirable. However, resistance is used in many varied ways. RESISTORS are components manufactured to possess specific values of resistance. They are manufactured in many types and sizes. When drawn using its schematic representation, a resistor is shown as a series of jagged lines, as illustrated in figure 3.

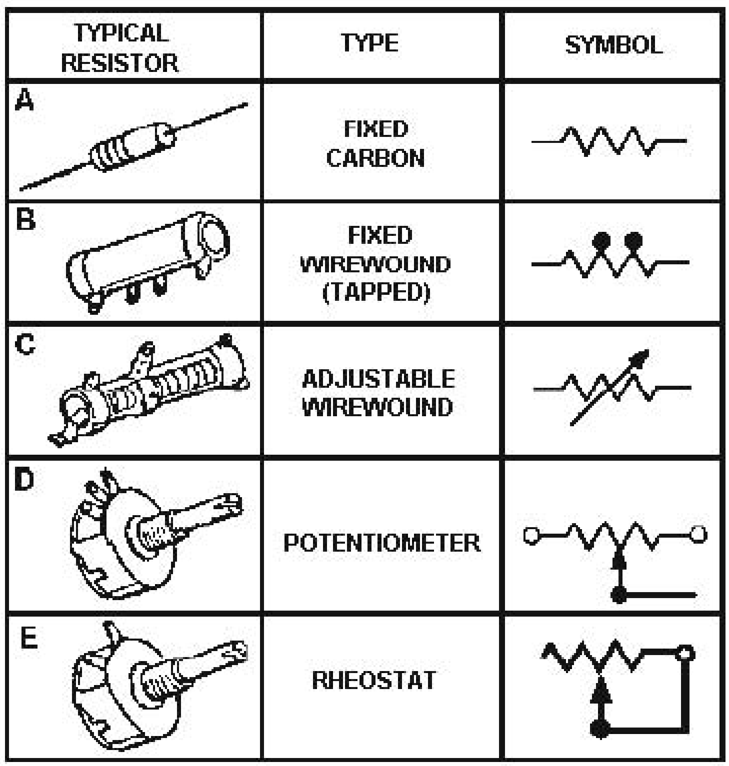

Figure 3.—Types of resistors.

☑Learning Check

9. What is the schematic symbol for a resistor?

Fixed and Variable Resistors

There are two kinds of resistors, FIXED and VARIABLE. The fixed resistor will have one value and will never change (other than through temperature, age, etc.). The resistors shown in A and B of figure 129 are classed as fixed resistors. The tapped resistor illustrated in B has several fixed taps and makes more than one resistance value available. The sliding contact resistor shown in C has an adjustable collar that can be moved to tap off any resistance within the ohmic value range of the resistor.

There are two types of variable resistors, one called a POTENTIOMETER and the other a RHEOSTAT (see views D and E of fig. 3.) An example of the potentiometer is the volume control on your radio, and an example of the rheostat is the dimmer control for the dash lights in an automobile. There is a slight difference between them. Rheostats usually have two connections, one fixed and the other moveable. Any variable resistor can properly be called a rheostat. The potentiometer always has three connections, two fixed and one moveable. Generally, the rheostat has a limited range of values and a high current-handling capability. The potentiometer has a wide range of values, but it usually has a limited current-handling capability. Potentiometers are always connected as voltage dividers.

☑**Learning Check**

10. Describe the differences between the rheostat connections and those of the potentiometer.

11. Which type of variable resistor should you select for controlling a large amount of current?

Wattage Rating

When a current is passed through a resistor, heat is developed within the resistor. The resistor must be capable of dissipating this heat into the surrounding air; otherwise, the temperature of the resistor rises causing a change in resistance, or possibly causing the resistor to burn out.

The ability of the resistor to dissipate heat depends upon the design of the resistor itself. This ability to dissipate heat depends on the amount of surface area which is exposed to the air. A resistor designed to dissipate a large amount of heat must therefore have a large physical size. The heat dissipating capability of a resistor is measured in WATTS (this unit will be explained later in chapter 3). Some of the more common wattage ratings of carbon resistors are: one-eighth watt, one-fourth watt, one-half watt, one watt, and two watts. In some of the newer state-of-the-art circuits of today, much smaller wattage resistors are used. Generally, the types that you will be able to physically work with are of the values given. The higher the wattage rating of the resistor the larger is the physical size. Resistors that dissipate very large amounts of power (watts) are usually wirewound resistors. Wirewound resistors with wattage ratings up to 50 watts are not uncommon.

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CHAPTER 2: DIRECT CURRENT

Learning Objectives

Upon completing this section, you will be able to:

- Identify the term schematic diagram and identify the components in a circuit from a simple schematic diagram;
- State the equation for Ohm's law and describe the effects on current caused by changes in a circuit;
- Identify the term power, and state three formulas for computing power;
- Compute circuit and component power in series and parallel circuits;
- Solve for unknown quantities of resistance, current, and voltage in a series circuit;
- Solve for unknown quantities of resistance, current, and voltage in a parallel circuit; and
- State the meaning of the term equivalent resistance.

Introduction

The material covered in this section contains many new terms that are explained as you progress through the material. The basic dc circuit is the easiest to understand, so the chapter begins with the basic circuit and from there works into the basic schematic diagram of that circuit. The schematic diagram is used in all your future work in electricity and electronics. It is very important that you become familiar with the symbols that are used.

This section also explains how to determine the total resistance, current, voltage, and power in a series and parallel circuits through the use of Ohm's and Kirchhoff's laws

The Basic Electrical Circuit

The flashlight is an example of a basic electric circuit. It contains a source of electrical energy (the dry cells in the flashlight), a load (the bulb) which changes the electrical energy into a more useful form of energy (light), and a switch to control the energy delivered to the load.

Before you study a schematic representation of the flashlight, it is necessary to define certain terms. The LOAD is any device through which an electrical current flows and which changes this electrical energy into a more useful form. Some common examples of loads are a lightbulb, which changes electrical energy to light energy; an electric motor, which changes electrical energy into mechanical energy; and the speaker in a radio, which changes electrical energy into sound. The SOURCE is the device which furnishes the electrical energy used by the load. It may consist of a simple dry cell (as in a flashlight), a storage battery (as in an automobile), or a power supply (such as a battery charger). The SWITCH, which permits control of the electrical device, interrupts the current delivered to the load.

Schematic Representation

The technician's main aid in troubleshooting a circuit in a piece of equipment is the SCHEMATIC DIAGRAM. The schematic diagram is a "picture" of the circuit that uses symbols to represent the various circuit components; physically large or complex circuits can be shown on a relatively small diagram. Before studying the basic schematic, look at figure 4. This figure shows the symbols that are used in this chapter. These, and others like them, are referred to and used throughout the study of electricity and electronics.

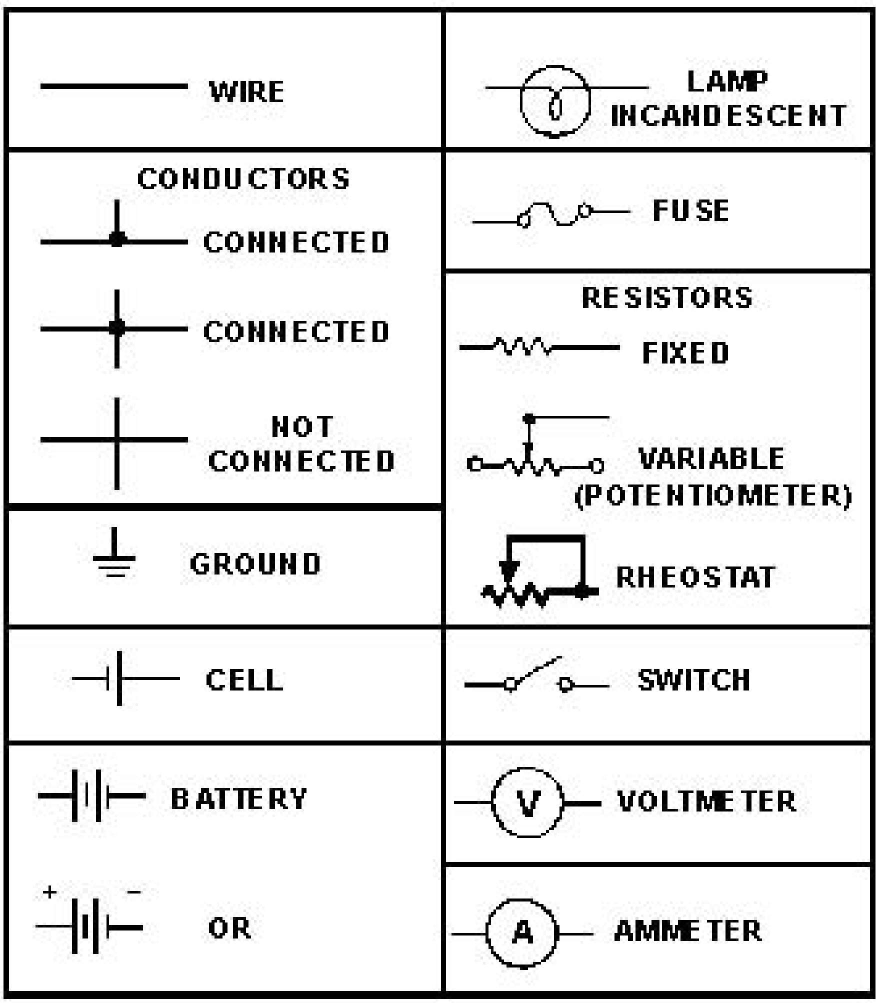


Figure 4.—Symbols commonly used in electricity.

The schematic in figure 5 represents a flashlight. View A of the figure shows the flashlight in the off or deenergized state. The switch (S1) is open. There is no complete path for current (I) through the circuit, and the bulb (DS1) does not light. In figure 5 view B, switch S1 is closed. Current flows in the direction of the arrows from the negative terminal of the battery (BAT), through the switch (S1), through the lamp (DS1), and back to the positive terminal of the battery. With the switch closed the path for current is complete. Current will continue to flow until the switch (S1) is moved to the open position or the battery is completely discharged.

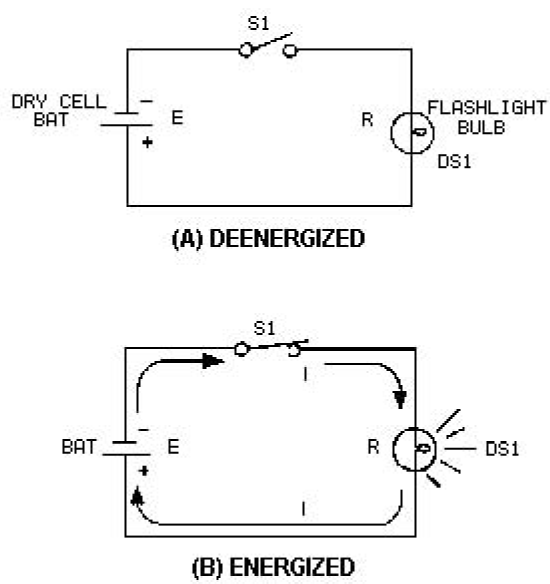


Figure 5.—Basic flashlight schematic.

☑Learning Check

12. In figure 5, what part of the circuit is the (a) load and (b) source?

13. What happens to the path for current when S1 is open as shown in figure 5(A)?

14. What is the name given to the "picture" of a circuit such as the one shown in figure 5?

OHM'S Law

The Law

In the early part of the 19th century, George Simon Ohm proved by experiment that a precise relationship exists between current, voltage, and resistance. This relationship is called Ohm's law and is stated as follows:

> "The current in a circuit is DIRECTLY proportional to the applied voltage and INVERSELY proportional to the circuit resistance".
>
> Ohm's law may be expressed as an equation: I=E/R

As stated in Ohm's law, current is inversely proportional to resistance. This means, as the resistance in a circuit increases, the current decreases proportionately.

In the equation if any two quantities are known, the third one can be determined. Refer to figure 5(B), the schematic of the flashlight. If the battery (BAT) supplies a voltage of 1.5 volts and the lamp (DS1) has a resistance of 5 ohms, then the current in the circuit can be determined. Using this equation and substituting values:

I=E/R

E=1.5v

R=5Ω

I=1.5/5 = 0.3 ampere

If the flashlight were a two-cell flashlight, we would have twice the voltage, or 3.0 volts, applied to the circuit. Using this voltage in the equation:

I=E/R

E=3.0v

R=5Ω

I=3.0/5 = 0.6 ampere

You can see that the current has doubled as the voltage has doubled. This demonstrates that the current is directly proportional to the applied voltage.

If the value of resistance of the lamp is doubled, the equation will be:

$$I = \frac{E}{R} = \frac{3.0 \text{ volts}}{10 \text{ ohms}} = .3 \text{ ampere}$$

The current has been reduced to one half of the value of the previous equation, or .3 ampere. This demonstrates that the current is inversely proportional to the resistance. Doubling the value of the resistance of the load reduces circuit current value to one half of its former value.

Application of Ohm's Law

By using Ohm's law, you are able to find the resistance of a circuit, knowing only the voltage and the current in the circuit.

In any equation, if all the variables (parameters) are known except one, that unknown can be found. For example, using Ohm's law, if current (I) and voltage (E) are known, resistance (R) the only parameter not known can be determined:

1. Basic formula:
2. Remove the divisor by multiplying both sides by R:
3. Result of step 2: R x I = E
4. To get R alone (on one side of the equation) divide both sides by I:
5. The basic formula, transposed for R, is:

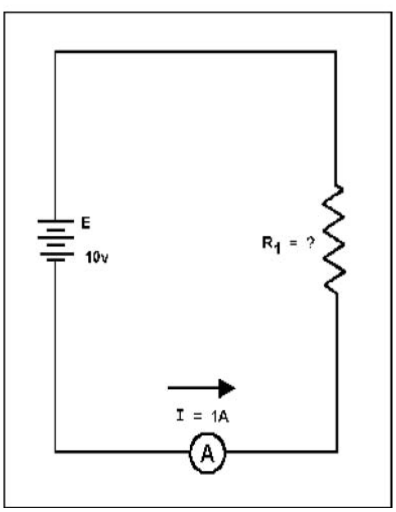
Refer to figure 6 where E equals 10 volts and I equals 1 ampere. Solve for R, using the equation just explained.

Given: E = 10 volts

I = 1 ampere

Solution:

$$R = \frac{E}{I}$$



Insert the values of the known quantities:

$$R = \frac{10 \text{ volts}}{1 \text{ ampere}}$$

$$R = 10 \text{ ohms}$$

The basic formula can also be used to solve for E:

Take the basic formula: $I = \dfrac{E}{R}$

multiply both sides by R:

$$I \times R = \frac{E}{R} \times \frac{R}{1}$$

Results $E = I \times R$

Figure 6.—Determining resistance in a basic circuit.

This equation can be used to find the voltage for the circuit shown in figure 7.

Given: $I = .5$ ampere
$R = 45$ ohms

Solution: $E = I \times R$
$E = .5 \text{ ampere} \times 45 \text{ ohms}$
$E = 22.5$ volts

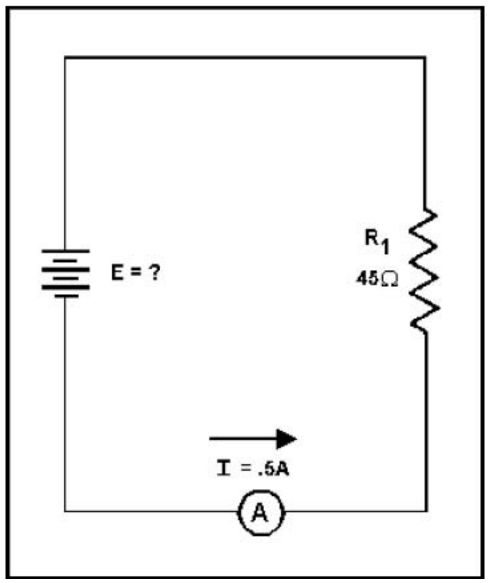


Figure 7.—Determining voltage in a basic circuit.

The Ohm's law equation and its various forms may be obtained readily with the aid of figure 8. The circle containing E, I, and R is divided into two parts, with E above the line and with I and R below the line. To determine the unknown quantity, first cover that quantity with a finger. The position of the uncovered letters in the circle will indicate the mathematical operation to be performed. For example, to find I, cover I with a finger. The uncovered letters indicate that E is to be divided by R, or

To find the formula for E, cover E with your finger. The result indicates that I is to be multiplied by R, or E = IR. To find the formula for R, cover R. The result indicates that E is to be divided by I, or

$$R = \frac{E}{I}$$

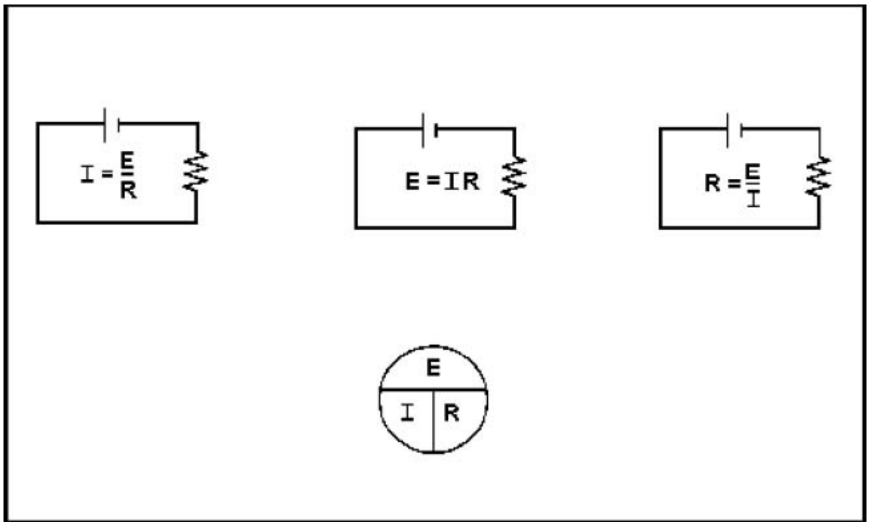


Figure 8.—Ohm's law in diagram form.

You are cautioned not to rely wholly on the use of this diagram when you transpose the Ohm's law formulas. The diagram should be used to supplement your knowledge of the algebraic method. Algebra is a basic tool in the solution of electrical problems.

☑Learning Check

15. According to Ohm's law, what happens to circuit current if the applied voltage (a) increases, (b) decreases?

16. According to Ohm's law, what happens to circuit current if circuit resistance (a) increases, (b) decreases?

17. What is the equation used to find circuit resistance if voltage and current values are known?

Power

Power, whether electrical or mechanical, pertains to the rate at which work is being done. Work is done whenever a force causes motion. When a mechanical force is used to lift or move a weight, work is done. However, force exerted WITHOUT causing motion, such as the force of a compressed spring acting between two fixed objects, does not constitute work.

Previously, it was shown that voltage is an electrical force, and that voltage forces current to flow in a closed circuit. However, when voltage exists but current does not flow because the circuit is open, no work is done. This is similar to the spring under tension that produced no motion. When voltage causes electrons to move, work is done. The instantaneous RATE at which this work is done is called the electric power rate, and is measured in WATTS.

A total amount of work may be done in different lengths of time. For example, a given number of electrons may be moved from one point to another in 1 second or in 1 hour, depending on the RATE at which they are moved. In both cases, total work done is the same. However, when the work is done in a short time, the wattage, or INSTANTANEOUS POWER RATE, is greater than when the same amount of work is done over a longer period of time.

As stated, the basic unit of power is the watt. Power in watts is equal to the voltage across a circuit multiplied by current through the circuit. This represents the rate at any given instant at which work is being done. The symbol P indicates electrical power. Thus, the basic power formula is $P = E \times I$, where E is voltage and I is current in the circuit. The amount of power changes when either voltage or current, or both voltage and current, are caused to change.

In practice, the ONLY factors that can be changed are voltage and resistance. In explaining the different forms that formulas may take, current is sometimes presented as a quantity that is changed. Remember, if current is changed, it is because either voltage or resistance has been changed.

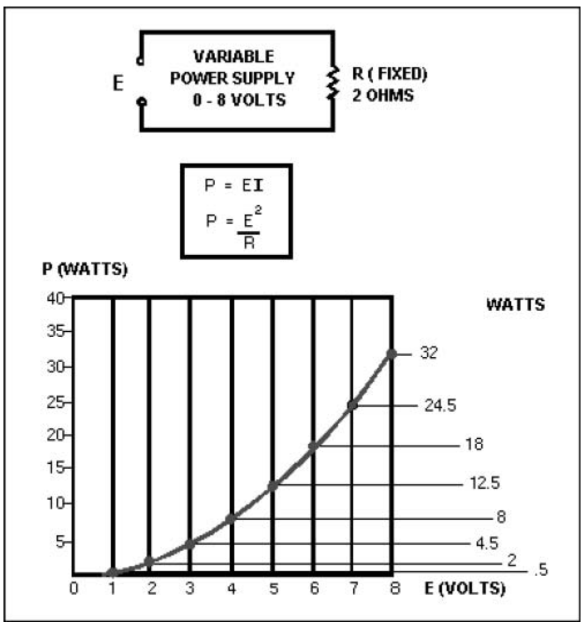
Figure 9 shows a basic circuit using a source of power that can be varied from 0 to 8 volts and a graph that indicates the relationship between voltage and power.

The resistance of this circuit is 2 ohms; this value does not change. Voltage (E) is increased (by increasing the voltage source), in steps of 1 volt, from 0 volts to 8 volts. By applying Ohm's law, the current (I) is determined for each step of voltage. For instance, when E is 1 volt, the current is:

$$I = \frac{E}{R}$$

$$I = \frac{1 \text{ volt}}{2 \text{ ohms}}$$

$$I = 0.5 \text{ ampere}$$



$$P = E \times I$$
$$P = 1 \text{ volt} \times 0.5 \text{ ampere}$$
$$P = 0.5 \text{ watt}$$

When E is increased to 2 volts:

$$I = \frac{E}{R}$$

$$I = \frac{2 \text{ volts}}{2 \text{ ohms}}$$

$$I = 1 \text{ ampere}$$

and P = E x I, P = 2 volts x 1 ampere P = 2 watts

Figure 9.—Graph of power related to changing voltage.

Power (P), in watts, is determined by applying the basic power formula:

P = I x E

When E is increased to 3 volts:

$$I = \frac{E}{R}$$

$$I = \frac{3 \text{ volts}}{2 \text{ ohms}}$$

$$I = 1.5 \text{ amperes}$$

and

$$P = E \times I$$
$$P = 3 \text{ volts} \times 1.5 \text{ ampere}$$
$$P = 4.5 \text{ watts}$$

You should notice that when the voltage was increased to 2 volts, the power increased from .5 watts to 2 watts or 4 times. When the voltage increased to 3 volts, the power increased to 4.5 watts or 9 times. This shows that if the resistance in a circuit is held constant, the power varies directly with the SQUARE OF THE VOLTAGE.

Another way of proving that power varies as the square of the voltage when resistance is held constant is: Another important relationship may be seen by studying figure 3-10. Thus far, power has been calculated with voltage and current (P = E x I), and with voltage and resistance:

Since: $I = \frac{E}{R}$

By substitution in: $P = E \times I$

You get: $P = E \times \frac{E}{R}$

Or: $P = \frac{E \times E}{R}$

Therefore: $P = \frac{E^2}{R}$

Referring to figure 10, note that power also varies as the square of current just as it does with voltage.

Thus, another formula for power, with current and resistance as its factors, is $P = I^2 R$. This can be proved by:

Since:	$E = I \times R$
By substituition in:	$P = E \times I$
You get:	$P = I \times R \times I$
Or:	$P = I \times I \times R$
Therefore:	$P = I^2 \times R$

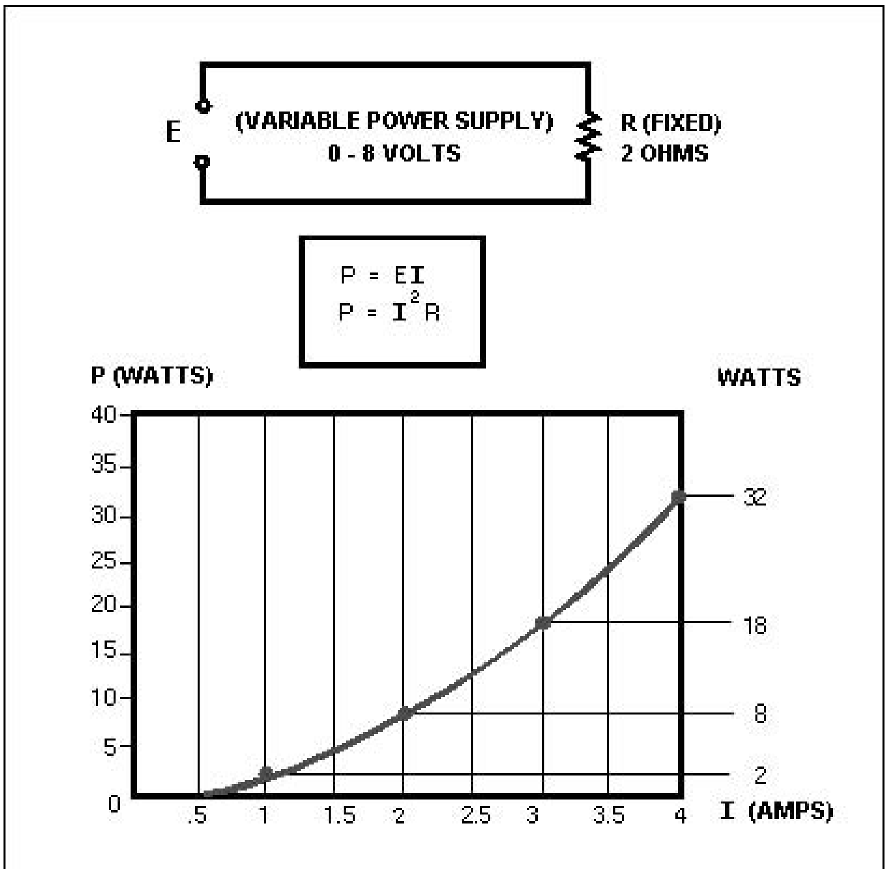


Figure 10.—Graph of power related to changing current.

Up to this point, four of the most important electrical quantities have been discussed. These are voltage (E), current (I), resistance(R), and power (P). You must understand the relationships which exist among these quantities because they are used throughout your study of electricity. In the preceding paragraphs, P was expressed in terms of alternate pairs of the other three basic quantities E, I, and R. In practice, you should be able to express any one of these quantities in terms of any two of the others.

Figure 11 is a summary of 12 basic formulas you should know. The four quantities E, I, R, and P are at the center of the figure. Adjacent to each quantity are three segments. Note that in each segment, the basic quantity is expressed in terms of two other basic quantities, and no two segments are alike.

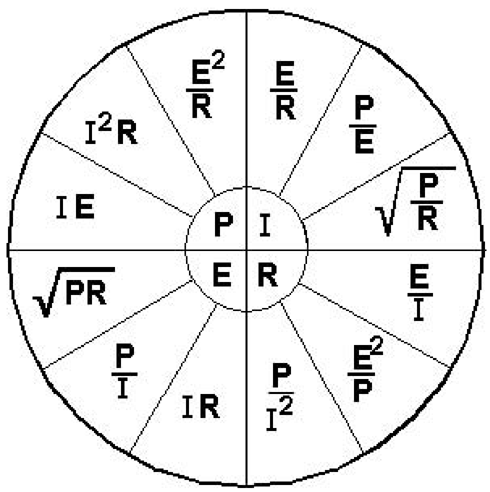


Figure 11.—Summary of basic formulas.

For example, the formula wheel in figure 11 could be used to find the formula to solve the following problem:

> A circuit has a voltage source that delivers 6 volts and the circuit uses 3 watts of power. What is the resistance of the load?
>
> Since R is the quantity you have been asked to find, look in the section of the wheel that has R in the center. The segment contains the quantities you have been given. The formula you would use is:

The problem can now be solved.

Given: $E = 6 \text{ volts}$
$P = 3 \text{ watts}$

Soultion: $R = \dfrac{E^2}{P}$

$$\frac{(6 \text{ volts})^2}{3 \text{ watts}}$$

$$R = \frac{36}{3} = 12 \text{ ohms}$$

☑**Learning Check**

18. What is the term applied to the rate at which a mechanical or electrical force causes motion?

19. How can the amount of current be changed in a circuit?

20. What are the three formulas for electrical power?

Power Rating

Electrical components are often given a power rating. The power rating, in watts, indicates the rate at which the device converts electrical energy into another form of energy, such as light, heat, or motion. An example of such a rating is noted when comparing a 150-watt lamp to a 100-watt lamp. The higher wattage rating of the 150-watt lamp indicates it is capable of converting more electrical energy into light energy than the lamp of the lower rating. Other common examples of devices with power ratings are soldering irons and small electric motors.

In some electrical devices the wattage rating indicates the maximum power the device is designed to use rather than the normal operating power. A 150-watt lamp, for example, uses 150 watts when operated at the specified voltage printed on the bulb. In contrast, a device such as a resistor is not normally given a voltage or a current rating. A resistor is given a power rating in watts and can be operated at any combination of voltage and current as long as the power rating is not exceeded. In most circuits, the actual power used by a resistor is considerably less than the power rating of the resistor because a 50% safety factor is used. For example, if a resistor normally used 2 watts of power, a resistor with a power rating of 3 watts would be used.

Resistors of the same resistance value are available in different wattage values. Carbon resistors, for example, are commonly made in wattage ratings of 1/8, ¼, ½, 1, and 2 watts. The larger the physical size of a carbon resistor the higher the wattage rating. This is true because a larger surface area of material radiates a greater amount of heat more easily.

When resistors with wattage ratings greater than 5 watts are needed, wirewound resistors are used. Wirewound resistors are made in values between 5 and 200 watts. Special types of wirewound resistors are used for power in excess of 200 watts.

As with other electrical quantities, prefixes may be attached to the word watt when expressing very large or very small amounts of power. Some of the more common of these are the kilowatt (1,000 watts), the megawatt (1,000,000 watts), and the milliwatt (1/1,000 of a watt).

☑**Learning Check**

21. What is the current in a circuit with 5 ohms of resistance that uses 180 watts of power? (refer to figure 12)

22. What type of resistor should be used in the circuit described in question 12?

23. What is the power used in a circuit that has 10 amperes of current through a 10-ohm resistor?

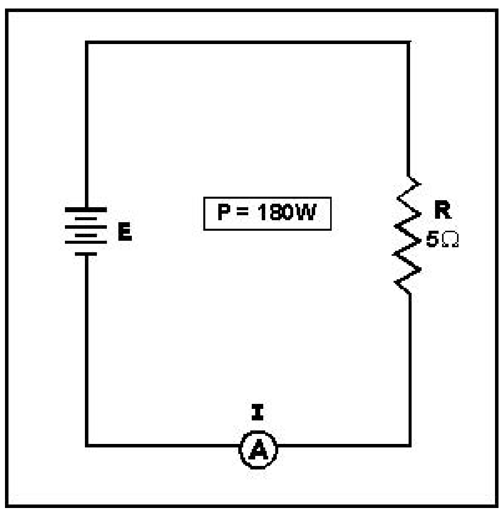


Figure 12.—Circuit for computing electrical quantities.

Series DC Circuits

When two unequal charges are connected by a conductor, a complete pathway for current exists. An electric circuit is a complete conducting pathway. It consists not only of the conductor, but also includes the path through the voltage source. Inside the voltage source current flows from the positive terminal, through the source, emerging at the negative terminal.

Series Circuit Characteristics

A SERIES CIRCUIT is defined as a circuit that contains only ONE PATH for current flow. To compare the basic circuit that has been discussed and a more complex series circuit, figure 13 shows two circuits. The basic circuit has only one lamp and the series circuit has three lamps connected in series.

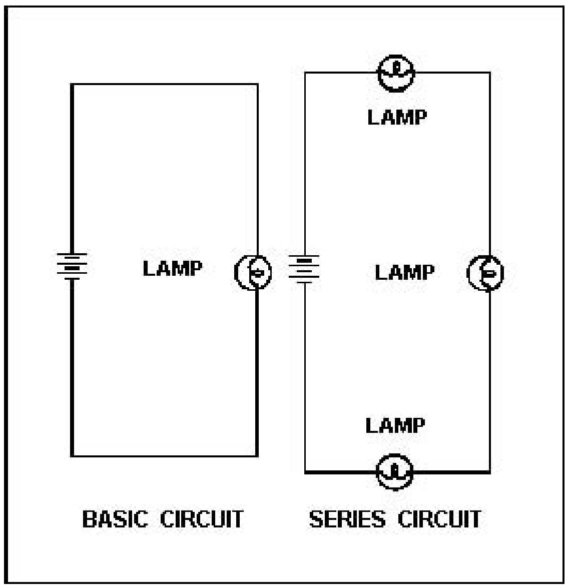


Figure 13.—Comparison of basic and series circuits.

Resistance in a Series Circuit

Referring to figure 13, the current in a series circuit must flow through each lamp to complete the electrical path in the circuit. Each additional lamp offers added resistance. In a series circuit, THE TOTAL CIRCUIT RESISTANCE (R_T) IS EQUAL TO THE SUM OF THE INDIVIDUAL RESISTANCES.

As an equation: $R_T = R_1 + R_2 + R_3 + \ldots R_n$

NOTE: The subscript n denotes any number of additional resistances that might be in the equation.

Example: In figure 14 a series circuit consisting of three resistors: one of 10 ohms, one of 15 ohms, and one of 30 ohms, is shown. A voltage source provides 110 volts. What is the total resistance?

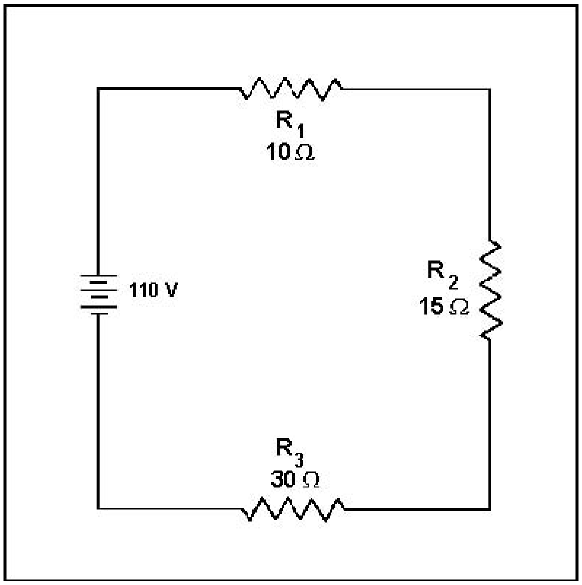


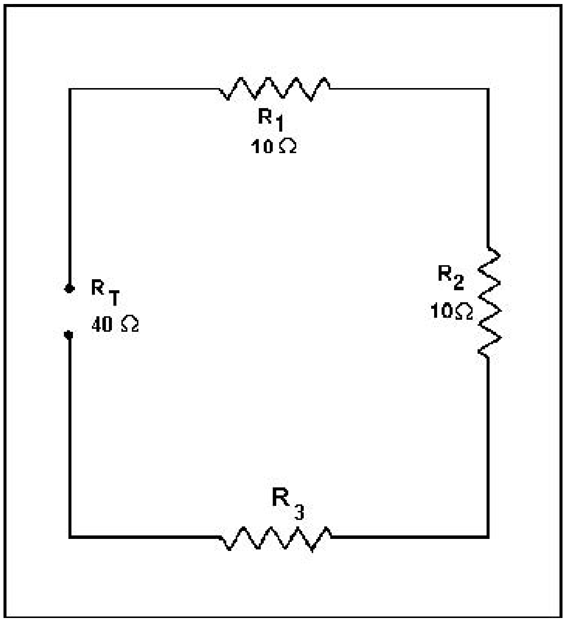
Figure 14.—Solving for total resistance in a series circuit.

Given: $R_1 = 10$ ohms
$R_2 = 15$ ohms
$R_3 = 30$ ohms

Soulution: $R_T = R_1 + R_2 + R_3$
$R_T = 10 \text{ ohms} + 15 \text{ ohms} + 30 \text{ ohms}$
$R_T = 55$ ohms

In some circuit applications, the total resistance is known and the value of one of the circuit resistors has to be determined. The equation $RT = R1 + R2 + R3$ can be transposed to solve for the value of the unknown resistance.

Example: In figure 15 the total resistance of a circuit containing three resistors is 40 ohms. Two of the circuit resistors are 10 ohms each. Calculate the value of the third resistor (R_3).



Given:

R_T= 40 ohms
R_2 = 10 ohms
R_3 = 10 ohms

Solution:

$$R_T = R_1 + R_2 + R_3$$

(Subtract $R_1 + R_2$ from both sides of the equation.)

$$R_T - R_1 - R_2 = R_3$$
$$R_3 = R_T - R_1 - R_2$$
$$R_3 = 40 \text{ ohms} - 10 \text{ ohms} - 10 \text{ ohms}$$
$$R_3 = 40 \text{ ohms} - 20 \text{ ohms}$$
$$R_3 = 20 \text{ ohms}$$

Figure 15.—Calculating the value of one resistance in a series circuit

Current in a Series Circuit

The fact that the same current flows through each component of a series circuit can be verified by inserting meters into the circuit at various points, as shown in figure 16. If this were done, each meter would be found to indicate the same value of current.

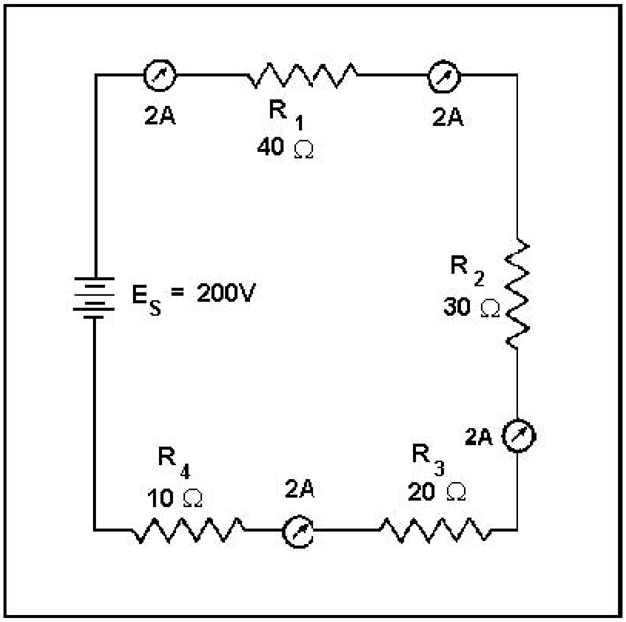
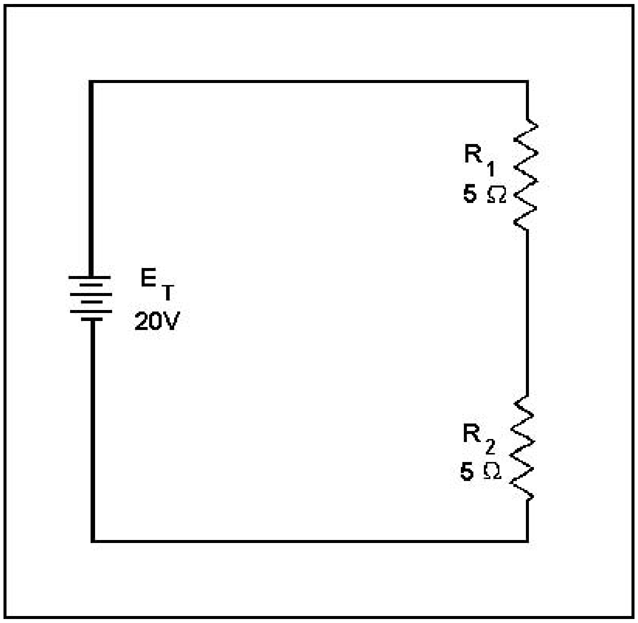


Figure 16.—Current in a series circuit

Voltage in a Series Circuit

The voltage dropped across the resistor in a circuit consisting of a single resistor and a voltage source is the total voltage across the circuit and is equal to the applied voltage. The total voltage across a series circuit that consists of more than one resistor is also equal to the applied voltage, but consists of the sum of the individual resistor voltage drops. In any series circuit, the SUM of the resistor voltage drops must equal the source voltage. This statement can be proven by an examination of the circuit shown in figure 17. In this circuit a source potential (E_T) of 20 volts is dropped across a series circuit consisting of two 5-ohm resistors. The total resistance of the circuit (R_T) is equal to the sum of the two individual resistances, or 10 ohms.

Using Ohm's law the circuit current may be calculated as follows:



Given: $E_T = 20$ volts
$R_T = 10$ ohms

Solution: $I_T = \dfrac{E_T}{R_T}$

$$I_T = \frac{20 \text{ volts}}{10 \text{ ohms}}$$

$$I_T = 2 \text{ amps}$$

Figure 17—Calculating individual voltage drops in a series circuit.

Since the value of the resistors is known to be 5 ohms each, and the current through the resistors is known to be 2 amperes, the voltage drops across the resistors can be calculated. The voltage (E_1) across R_1 is therefore:

By inspecting the circuit, you can see that R_2 is the same ohmic value as R_1 and carries the same current. The voltage drop across R_2 is therefore also equal to 10 volts. Adding these two 10-volts drops together gives a total drop of 20 volts, exactly equal to the applied voltage. For a series circuit then:

$$E_T = E_1 = E_2 + E_3 = \ldots E_n$$

Example: A series circuit consists of three resistors having values of 20 ohms, 30 ohms, and 50 ohms, respectively. Find the applied voltage if the current through the 30 ohm resistor is 2 amps. (The abbreviation amp is commonly used for ampere).

To solve the problem, a circuit diagram is first drawn and labeled (fig 18).

Substituting:

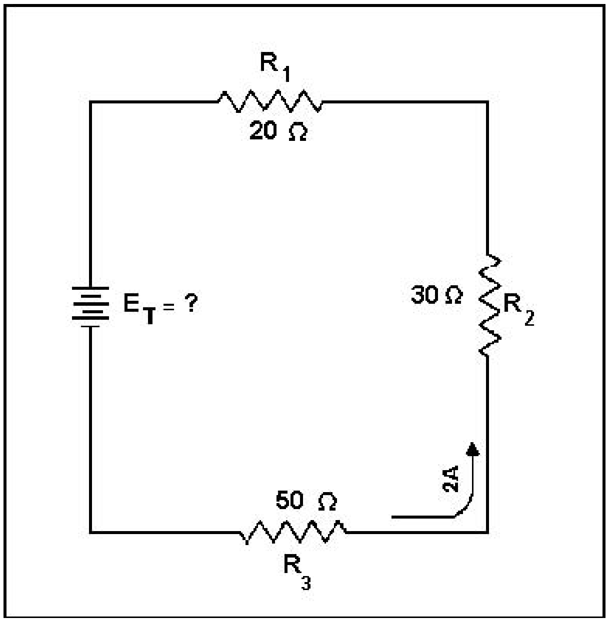


Figure 18.—Solving for applied voltage in a series circuit.

Given:

$R_1 = 20$ ohms
$R_2 = 30$ ohms
$R_3 = 50$ ohms
$I = 2$ amps

Solution:

$E_T = E_1 + E_2 + E_3$
$E_1 = R_1 \times I_1$ (I_1= The current through resistor R_1)
$E_2 = R_2 \times I_2$
$E_3 = R_3 \times I_3$

$$E_T = (R_1 \times I_1) + (R_2 \times I_2) + (R_3 \times I_3)$$

$$E_T = (20 \text{ ohms} \times 2 \text{ amps}) + (30 \text{ ohms} \times 2 \text{ amps}) + (50 \text{ ohms} \times 2 \text{ amps})$$

$$E_T = 40 \text{ volts} + 60 \text{ volts} + 100 \text{ volts}$$

$$E_T = 200 \text{ volts}$$

NOTE: When you use Ohm's law, the quantities for the equation MUST be taken from the SAME part of the circuit. In the above example the voltage across R2 was computed using the current through R2 and the resistance of R2.

The value of the voltage dropped by a resistor is determined by the applied voltage and is in proportion to the circuit resistances. The voltage drops that occur in a series circuit are in direct proportion to the resistances. This is the result of having the same current flow through each resistor–the larger the ohmic value of the resistor, the larger the voltage drop across it.

☑**Learning Check**

24. A series circuit consisting of three resistors has a current of 3 amps. If R_1 = 20 ohms, R_2= 60 ohms, and R_3 = 80 ohms, what is the (a) total resistance and (b) source voltage of the circuit?

25. What is the voltage dropped by each resistor of the circuit described in question 17?

26. If the current was increased to 4 amps, what would be the voltage drop across each resistor in the circuit described in question 17?

27. What would have to be done to the circuit described in question 17 to increase the current to 4 amps?

Parallel Circuit Characteristics

A PARALLEL CIRCUIT is defined as one having more than one current path connected to a common voltage source. Parallel circuits, therefore, must contain two or more resistances which are not connected in series. An example of a basic parallel circuit is shown in figure 19.

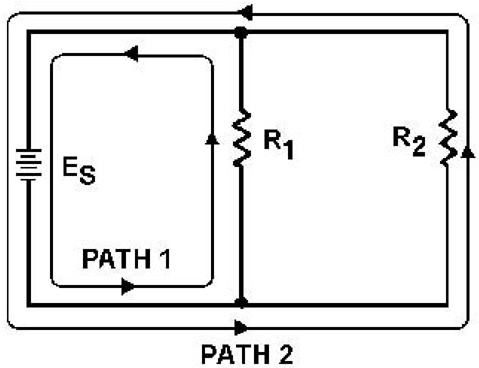


Figure 19.—Example of a basic parallel circuit

Start at the voltage source (E_S) and trace counterclockwise around the circuit. Two complete and separate paths can be identified in which current can flow. One path is traced from the source, through resistance R_1, and back to the source. The other path is from the source, through resistance R_2, and back to the source.

Voltage in a Parallel Circuit

You have seen that the source voltage in a series circuit divides proportionately across each resistor in the circuit. IN A PARALLEL CIRCUIT, THE SAME VOLTAGE IS PRESENT IN EACH BRANCH. (A branch is a section of a circuit that has a complete path for current.) In figure 19 this voltage is equal to the applied voltage (E_S). This can be expressed in equation form as:

$$E_S = E_{R1} = E_{R2}$$

Voltage measurements taken across the resistors of a parallel circuit, as illustrated by figure 20 verify this equation. Each meter indicates the same amount of voltage. Notice that the voltage across each resistor is the same as the applied voltage.

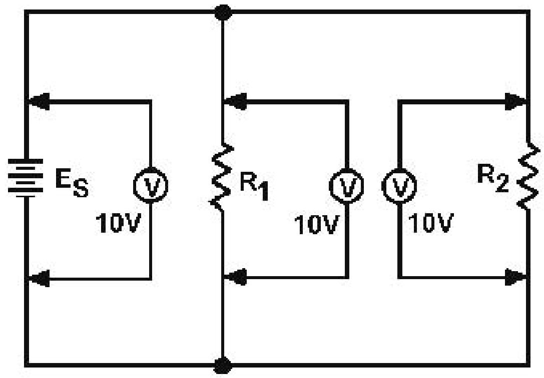


Figure 20.—Voltage comparison in a parallel circuit.

Example: Assume that the current through a resistor of a parallel circuit is known to be 4.5 voltage. The circuit is shown in figure 21.

Given: R_2 = 30,000 ohms (30kΩ)

I_{R2} = 4.5 milliamps (4.5 mA or .0045 amps)

E=IR

E_{R2} = .0045 amps x 30,000 ohms

E_{R2} = 135 volts

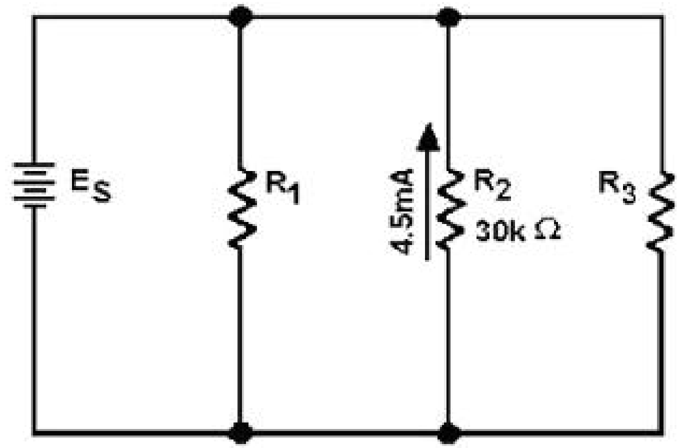


Figure 21.—Example problem parallel circuit.

Since the source voltage is equal to the voltage of a branch:

To simplify the math operation, the values can be expressed in powers of ten as follows:

$$30{,}000 \text{ ohms} = 30 \times 10^{3} \text{ ohms}$$
$$4.5\text{mA} = 4.5 \times 10^{-3} \text{ amps}$$
$$E_{R2} = (4.5 \times 10^{-3}) \text{ amps} \times (30 \times 10^{3}) \text{ ohms}$$
$$E_{R2} = (4.5 \times 30 \times 10^{-3} \times 10^{3}) \text{ volts}$$
$$(10^{-3} \times 10^{3} = 10^{-3+3} = 10^{0} = 1)$$
$$E_{R2} = (4.5 \times 30 \times 1) \text{ volts}$$
$$E_{R2} = 135 \text{ volts}$$
$$E_{S} = E_{R2}$$
$$E_{S} = 135 \text{ volts}$$

☑**Learning Check**

28. What would the source voltage (ES) in figure 21 be if the current through R2 were 2 milliamps?

Current in a Parallel Circuit

Ohm's law states that the current in a circuit is inversely proportional to the circuit resistance. This fact is true in both series and parallel circuits.

There is a single path for current in a series circuit. The amount of current is determined by the total resistance of the circuit and the applied voltage. In a parallel circuit the source current divides among the available paths.

The behavior of current in parallel circuits will be shown by a series of illustrations using example circuits with different values of resistance for a given value of applied voltage.

Part (A) of figure 22 shows a basic series circuit. Here, the total current must pass through the single resistor. The amount of current can be determined.

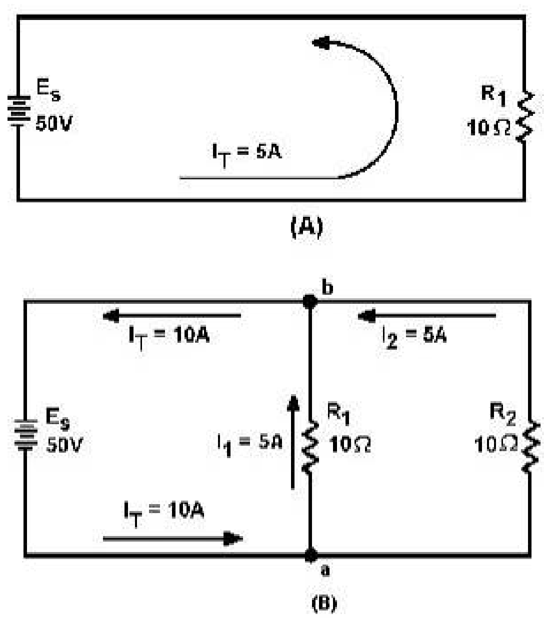


Figure 22.—Analysis of current in parallel circuit.

Given: $E_s = 50$ volts

$R_1 = 10$ ohms

Solution: $I = E/R$

$I_T = E_s/R_1$

$I_T = 50$ volts/10 ohms

$I_T = 5$ amps

Part (B) of figure 22 shows the same resistor (R1) with a second resistor (R2) of equal value connected in parallel across the voltage source. When Ohm's law is applied, the current flow through each resistor is found to be the same as the current through the single resistor in part (A).

Given: $E_s = 50$ volts

$R_1 = 10$ ohms

$R_2 = 10$ ohms

Solution: $I = E/R$

$E_s = E_{R1} = E_{R2}$

$I_{R1} = E_{R1} / R_1$

$I_{R1} = 50$ volts/ 10 ohms

$I_{R1} = 5$ amps

$I_{R2} = E_{R2} / R_2$

$I_{R2} = 50$ volts/ 10 ohms

$I_{R2} = 5$ amps

It is apparent that if there is 5 amperes of current through each of the two resistors, there must be a TOTAL CURRENT of 10 amperes drawn from the source.

The total current of 10 amperes, as illustrated in figure 22(B), leaves the negative terminal of the battery and flows to point a. Since point a is a connecting point for the two resistors, it is called a JUNCTION. At junction a, the total current divides into two currents of 5 amperes each. These two currents flow through their respective resistors and rejoin at junction b. The total current then flows from junction b back to the positive terminal of the source. The source supplies a total current of 10 amperes and each of the two equal resistors carries one-half the total current.

Each individual current path in the circuit of figure 22(B) is referred to as a BRANCH. Each branch carries a current that is a portion of the total current. Two or more branches form a NETWORK.

From the previous explanation, the characteristics of current in a parallel circuit can be expressed in terms of the following general equation:

$$I_T = I_1 + I_2 + \ldots I_n$$

Compare part (A) of figure 23 with part (B) of the circuit in figure 23. Notice that doubling the value of the second branch resistor (R_2) has no effect on the current in the first branch (I_{R1}), but does reduce the second branch current (I_{R2}) to one-half its original value. The total circuit current drops to a value equal to the sum of the branch currents. These facts are verified by the following equations

Given: $E_s = 50$ volts
$R_1 = 10$ ohms
$R_2 = 20$ ohms

Solution: $I = E/R$
$E_s = E_{R1} = E_{R2}$
$I = E_{R1} / R_1$
$I = 50$ volts / 10 ohms
$I_{R1} = 5$ amps

$I_{R2} = E_{R2} / R_2$
$I_{R2} = 50$ volts / 20 ohms
$I_{R2} = 2.5$ amps

$I_T = I_{R1} + I_{R2}$
$I_T = 5$ amps + 2.5 amps
$I_T = 7.5$ amps

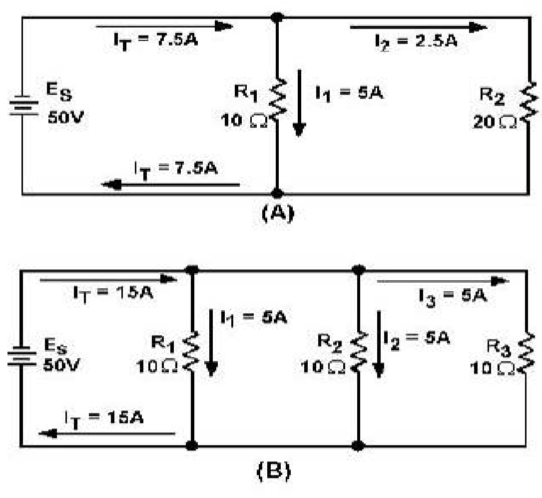


Figure 23.—Current behavior in parallel circuits.

The amount of current flow in the branch circuits and the total current in the circuit shown in figure 23(B) are determined by the following computations.

Given: $I = E/R$
$E_s = E_{R1} = E_{R2} = E_{R3}$

Solution: $I_{R1} = E_{R1}/ R_1$
$I_{R1} = 50 \text{ volts} / 10 \text{ ohms}$
$I_{R1} = 5 \text{ amps}$

$I_{R2} = E_{R2}/ R_2$
$I_{R2} = 50 \text{ volts} / 10 \text{ ohms}$
$I_{R2} = 5 \text{ amps}$

$I_{R3} = E_{R3}/ R_3$
$I_{R3} = 50 \text{ volts} / 10 \text{ ohms}$
$I_{R3} = 5 \text{ amps}$

$I_T = I_{R1} + I_{R2} + I_{R3}$
$I_T = 5 \text{ amps} + 5 \text{ amps} + 5 \text{ amps}$
$I_T = 15 \text{ amps}$

Resistance in a Parallel Circuit

In the example diagram, figure 24, there are two resistors connected in parallel across a 5-volt battery. Each has a resistance value of 10 ohms. A complete circuit consisting of two parallel paths is formed and current flows as shown.

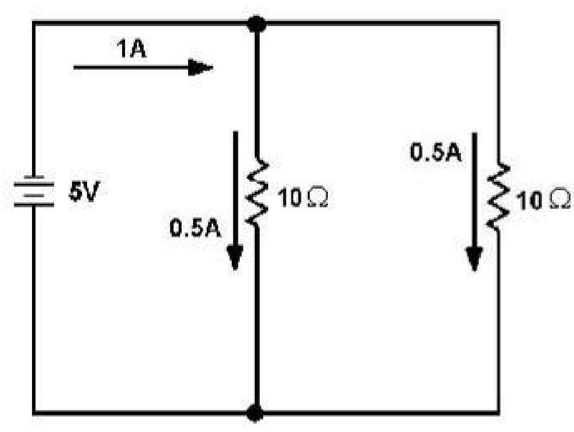


Figure 24.—Two equal resistors connected in parallel

Computing the individual currents shows that there is one-half of an ampere of current through each resistance. The total current flowing from the battery to the junction of the resistors, and returning from the resistors to the battery, is equal to 1 ampere.

The total resistance of the circuit can be calculated by using the values of total voltage (ET) and total current (IT).

NOTE: From this point on the abbreviations and symbology for electrical quantities will be used in example problems.

Given: $I_T = E_t / R_t$
$R_T = E_T / I_T$

Solution: $R_T = 5 \text{ v} / 1 \text{ a}$
$R_T = 5\ \Omega$

This computation shows the total resistance to be 5 ohms; one-half the value of either of the two resistors.

Since the total resistance of a parallel circuit is smaller than any of the individual resistors, total resistance of a parallel circuit is not the sum of the individual resistor values as was the case in a series circuit. The total resistance of resistors in parallel is also referred to as EQUIVALENT RESISTANCE (Req). The terms total resistance and equivalent resistance are used interchangeably.

There are several methods used to determine the equivalent resistance of parallel circuits. The best method for a given circuit depends on the number and value of the resistors. For the circuit described above, where all resistors have the same value, the following simple equation is used:

This equation is valid for any number of parallel resistors of EQUAL VALUE.

Example: Four 40-ohm resistors are connected in parallel. What is their equivalent resistance?

Given:

$$R_1 + R_2 + R_3 + R_4$$
$$R_1 = 40\ \Omega$$

Solution:

$$R_{eq} = \frac{R}{N}$$
$$R_{eq} = \frac{40\Omega}{4}$$
$$R_{eq} = 10\ \Omega$$

Figure 25 shows two resistors of unequal value in parallel. Since the total current is shown, the equivilent resistance can be calculated.

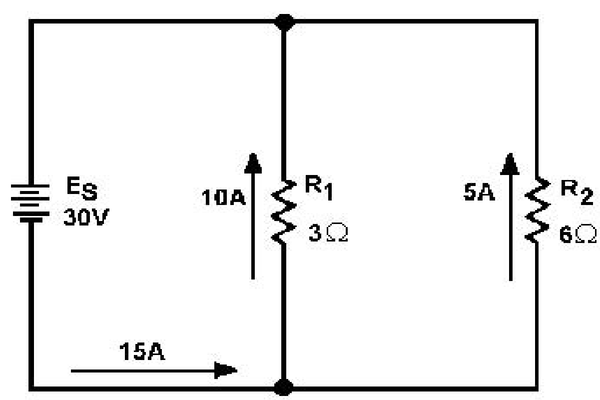


Figure 25.—Example circuit with unequal parallel resistors.

Given: $E_S = 30\ V$
$I_T = 15\ A$

Solution:

$$R_{eq} = \frac{E_S}{I_T}$$

$$R_{eq} = \frac{30\ V}{15\ A}$$

$$R_{eq} = 2\ \Omega$$

The equivalent resistance of the circuit shown in figure 25 is smaller than either of the two resistors (R_1, R_2). An important point to remember is that the equivalent resistance of a parallel circuit is <u>always less than the resistance of any branch</u>.

Equivalent resistance can be found if you know the individual resistance values and the source voltage. By calculating each branch current, adding the branch currents to calculate total current, and dividing the source voltage by the total current, the total can be found. This method, while effective, is somewhat lengthy. A quicker method of finding equivalent resistance is to use the general formula for resistors in parallel:

If you apply the general formula to the circuit shown in figure 26 you will get the same value for current.

Given: $R_1 = 3\Omega$
$R_2 = 6\Omega$

Solution:

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\frac{1}{R_{eq}} = \frac{1}{3\Omega} + \frac{1}{6\Omega}$$

Convert the fractions to a common denominator.

Since both sides are reciprocals (divided into one), disregard the reciprocal function.

The formula you were given for equal resistors in parallel is a simplification of the general formula for resistors in parallel

There are other simplifications of the general formula for resistors in parallel which can be used to calculate the total or equivalent resistance in a parallel circuit.

RECIPROCAL METHOD—this method is based upon taking the reciprocal of each side of the equation. This presents the general formula for resistors in parallel as:

Example: Three resistors are connected in parallel as shown in figure 26. The resistor values are: R_1 = 20 ohms, R_2 = 30 ohms, R_3 = 40 ohms. What is the equivalent resistance? (Use the reciprocal method.)

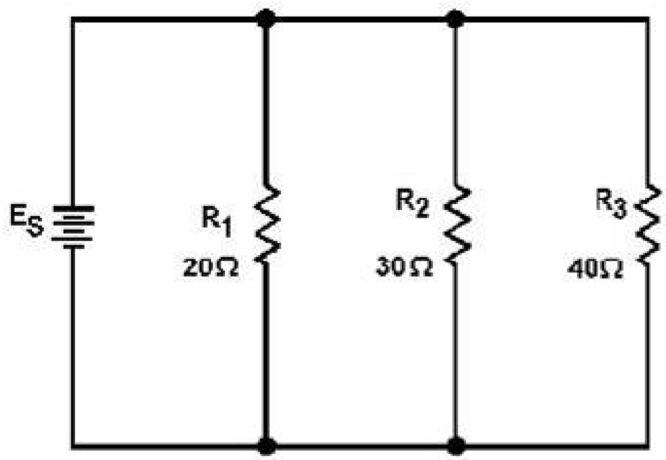


Figure 26.—Example parallel circuit with unequal branch resistors.

Given:

$$R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R3}}$$

Solution:

$$R_{eq} = \frac{1}{\frac{1}{20\Omega} + \frac{1}{30\Omega} + \frac{1}{40\Omega}}$$

$$R_{eq} = \frac{1}{\frac{6}{120\Omega} + \frac{4}{120\Omega} + \frac{3}{120\Omega}}$$

$$R_{eq} = \frac{1}{\frac{13}{120}\Omega}$$

$$R_{eq} = \frac{120}{13}\Omega$$

$$R_{eq} = 9.23\Omega$$

PRODUCT OVER THE SUM METHOD.—A convenient method for finding the equivalent, or total, resistance of two parallel resistors is by using the following formula.

This equation, called the product over the sum formula, is used so frequently it should be committed to memory.

Example: What is the equivalent resistance of a 20-ohm and a 30-ohm resistor connected in parallel, as in figure 27?

Given:

$$R_1 = 20\Omega$$
$$R_2 = 30\Omega$$

Solution:

$$R_{eq} = \frac{R_1 \times R_2}{R_1 + R_2}$$
$$R_{eq} = \frac{20\Omega \times 30\Omega}{20\Omega + 30\Omega}$$
$$R_{eq} = \frac{600}{50}\Omega$$
$$R_{eq} = 12\Omega$$

☑**Learning Check**

29. Four equal resistors are connected in parallel; each resistor has an ohmic value of 100 ohms, what is the equivalent resistance?

SUMMARY AND EVALUATION OF TRAINING

Summary

You have completed this workbook, and now you should be able to

- State, using the water analogy, how a difference of potential (a voltage or an electromotive force) can exist. Convert volts to microvolts, to millivolts, and to kilovolts;
- State the meanings of electron current, directed drift, and ampere, and indicate the direction that an electric current flows;
- State the relationship of current to voltage and convert amperes to milliamperes and microamperes; and
- State the definitions of and the terms and symbols for resistance and conductance, and how the temperature, contents, length and cross-sectional area of a conductor affect its resistance and conductance values.

Evaluation of Training

We value your input and we need your help in making this a better instructional product. Please complete the training evaluation form found on the next page. Be sure to leave the form in the workbook as it will be collected when you attend the Communications Specialist Course.

Now you can proceed to Volume 2: Radio Wave Propagation.

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Evaluation of Training
Volume 1: Matter, Energy, and DC Circuits

Date: ___________________

1. Were the objectives accomplished?	**Y**	**N**
Comments:		
2. Were the topics and exercises applicable and relevant to your job?	**Y**	**N**
Identify by name:		
3. Was there material presented that you felt was NOT applicable to your job (i.e., not useful information)?	**Y**	**N**
Identify topics:		
4. Did the sequencing of the instruction seem appropriate (i.e., was there a logical flow)?	**Y**	**N**
Comments:		
5. Did the learning checks effectively evaluate your accomplishment of the objectives?	**Y**	**N**
Comments:		
6. Did you feel the content was adequately covered without overkill?	**Y**	**N**
Comments:		

Please write any additional comments and suggestions:

PREFACE

Volume 2 of this workbook is intended to help you become familiar with basic electricity and electronics. It is not a requirement that you fully understand 100 percent of its content; however this information is the foundation of the US&R Communications Specialist (COMS) duties and will not be presented at this level during the course. Read and perform all activities, within the workbook prior to the class. The workbook may be used for "reference" throughout the course. This includes its use during the final 100 question exam, which includes 10 questions from this workbook.

ACKNOWLEDGEMENTS

This workbook was prepared with the help, advice, and assistance of personnel from many local, state, and federal agencies. Materials were drawn from previously published documents. Most of the workbook's content was extracted from the United States Navy Electricity and Electronics Training Series.

TABLE OF CONTENTS

TITLE PAGE

USING THIS WORKBOOK

Time to Complete

This workbook will take approximately eight hours to complete. This workbook has to be completed prior to attending the Communications Specialist Course. You will also need to bring this workbook to class with you, because it will become part of the manual you will have compiled by the end of the course.

While working through the workbooks read the learning objectives. The learning objectives state what you should be able to do after studying the material and the final course test is based on these objectives.

Learning Checks

You will find learning checks in the form of questions or equations at the end of critical knowledge areas. These learning checks are designed to help you understand the material found in the text. Plus, answering the questions correctly helps you accomplish the objectives. The answer key to the learning checks can be found in the back of this workbook.

STUDENT EVALUATION OF TRAINING (FEEDBACK)

We value your suggestions, questions, and criticisms concerning this workbook. Please complete the workbook evaluation form found at the end. This form can be turned in when you attend the Communications Specialist Course.

IF YOU NEED HELP

If you have any questions concerning the technical content please contact the individual whose email address was provided in the workbook cover letter.

CHAPTER 1: RADIO WAVE PROPAGATION

Learning Objectives

Upon completing this chapter, you will be able to

- State what radio waves are;
- List the components of a radio wave and define the terms cycle, frequency, harmonics, period, wavelength, and velocity as applied to radio wave propagation;
- Compute the wavelength of radio waves;
- State how radio waves are polarized, vertically and horizontally;
- State what reflection, refraction, and diffraction are as applied to radio waves;
- State what influence the Earth's atmosphere has on radio waves and list the different layers of the Earth's atmosphere;
- Identify a ground wave, a sky wave, and state the effects of the ionosphere on the sky wave;
- Describe propagation paths;
- Describe fading, multipath fading;
- Describe propagation paths;
- State how transmission losses affect radio wave propagation;
- State how electromagnetic interference, man-made/natural interference, and ionospheric disturbances affect radio wave propagation. State how transmission losses affect radio wave propagation;
- State what temperature inversion is, how frequency predictions are made, and how weather affects frequency; and
- State what tropospheric scatter is and how it affects radio wave propagation.

Introduction to Wave Propagation

Of the many technical subjects that Communication Specialists are expected to know, the one least susceptible to change is the theory of wave propagation. The basic principles that enable waves to be propagated (transmitted) through space are the same today as they were 70 years ago. One would think, then, that a thorough understanding of these principles is a relatively simple task. For the electrical engineer or the individual with a natural curiosity for the unknown, it is indeed a simple task. Most technicians, however, tend to view wave propagation as something complex and confusing, and would just as soon see this chapter completely disappear from training manuals. This attitude undoubtedly stems from the fact that wave propagation is an invisible force that cannot be detected by the sense of sight or touch. Understanding wave propagation requires the use of the imagination to visualize the associated concepts and how they are used in practical application. This manual was developed to help you visualize and understand those concepts. Through ample use of illustrations and a step-by-step transition from the simple to the complex, we will help you develop a better understanding of wave propagation. In this chapter, we will discuss propagation theory on an introductory level, without going into the technical details that concern the engineer. However, you must still use thought and imagination to understand the new ideas and concepts as they are presented.

To understand radio wave propagation, you must first learn what wave propagation is and some of the basic physics or properties that affect propagation. Many of these properties are common everyday occurrences, with which you are already familiar.

What is Propagation?

Early man was quick to recognize the need to communicate beyond the range of the human voice. To satisfy this need, he developed alternate methods of communication, such as hand gestures, beating on a hollow log, and smoke signals. Although these methods were effective, they were still greatly limited in range. Eventually, the range limitations were overcome by the development of courier and postal systems; but there was then a problem of speed. For centuries the time required for the delivery of a message depended on the speed of a horse.

During the latter part of the 19th century, both distance and time limitations were largely overcome. The invention of the telegraph made possible instantaneous communication over long wires. Then a short time later, man discovered how to transmit messages in the form of RADIO WAVES.

As you will learn in this chapter, radio waves are propagated. PROPAGATION means "movement through a medium." This is most easily illustrated by light rays. When a light is turned on in a darkened room, light rays travel from the light bulb throughout the room. When a flashlight is turned on, light rays also radiate from its bulb, but are focused into a narrow beam. You can use these examples to picture how radio waves propagate. Like the light in the room, radio waves may spread out in all directions. They can also be focused (concentrated) like the flashlight, depending upon the need. Radio waves are a form of radiant energy, similar to light and heat. Although they can neither be seen nor felt, their presence can be detected through the use of sensitive measuring devices. The speed at which both forms of waves travel is the same; they both travel at the speed of light.

You may wonder why you can see light but not radio waves, which consist of the same form of energy as light. The reason is that you can only "see" what your eyes can detect. Your eyes can detect radiant energy only within a fixed range of frequencies. Since the frequencies of radio waves are below the frequencies your eyes can detect, you cannot see radio waves.

The theory of wave propagation that we discuss in this section applies to communication equipment.

Electromagnetic Spectrum

Light is one kind of electromagnetic energy. There are many other types, including heat energy and radio energy. The only difference between the various types of electromagnetic energy is the frequency of their waves (rate of vibration). The term SPECTRUM is used to designate the entire range of electromagnetic waves arranged in order of their frequencies. The VISIBLE SPECTRUM contains only those waves which stimulate the sense of sight. You, as a technician, might be expected to maintain equipment that uses electromagnetic waves within, above, and below the visible spectrum.

There are neither sharp dividing lines nor gaps in the ELECTROMAGNETIC SPECTRUM. Figure 1-1 illustrates how portions of the electromagnetic spectrum overlap. Notice that only a small portion of the electromagnetic spectrum contains visible waves, or light, which can be seen by the human eye.

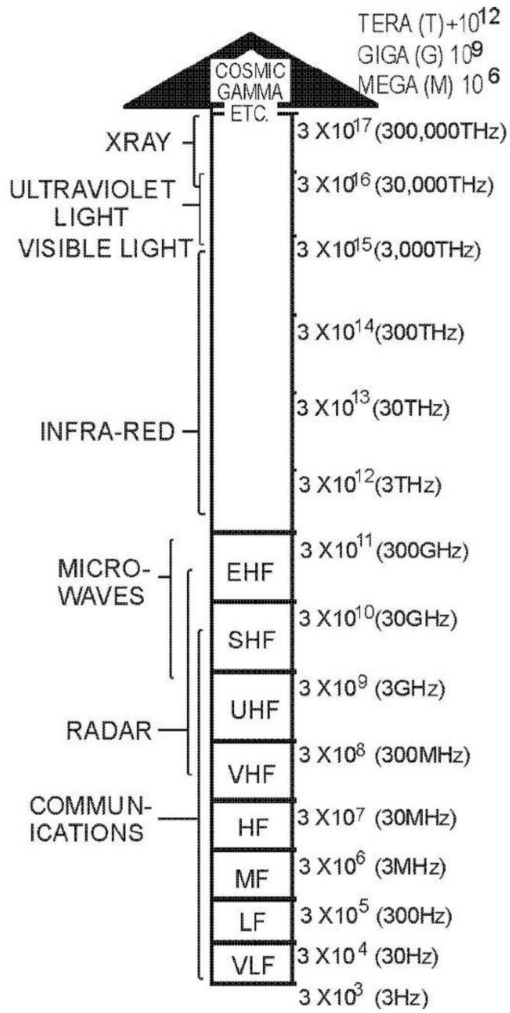

Figure 1-1.—Electromagnetic spectrum.

Electromagnetic Waves

In general, the same principles and properties of light waves apply to the communications electromagnetic waves you are about to study. The electromagnetic field is used to transfer energy (as communications) from point to point. We will introduce the basic ANTENNA as the propagation source of these electromagnetic waves.

The Basic Antenna

The study of antennas and electromagnetic wave propagation is essential to a complete understanding of radio communication, radar, loran, and other electronic systems. Figure 1-2 shows a simple radio communication system. In the illustration, the transmitter is an electronic device that generates radio-frequency energy. The energy travels through a transmission line (we will discuss this in chapter 3) to an antenna. The antenna converts the energy into radio waves that radiate into space from the antenna at the speed of light. The radio waves travel through the atmosphere or space until they are either reflected by an object or absorbed. If another antenna is placed in the path of the radio waves, it absorbs part of the waves and converts them to energy. This energy travels through another transmission line and is fed to a receiver. From this example, you can see that the requirements for a simple communications system are (1) transmitting equipment, (2) transmission line, (3) transmitting antenna, (4) medium, (5) receiving antenna, and (6) receiving equipment.

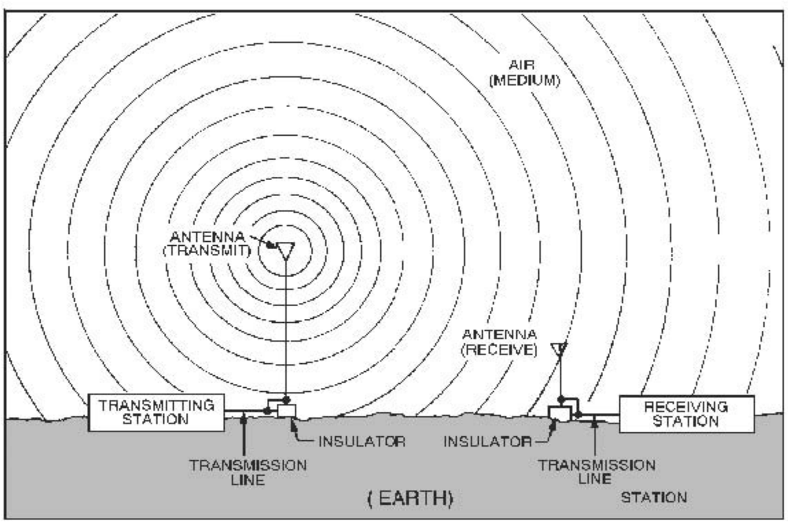

Figure 1-2.—Simple radio communication system.

An antenna is a conductor or a set of conductors used either to radiate electromagnetic energy into space or to collect this energy from space. Figure 1-3 shows an antenna. View A is a drawing of an actual antenna; view B is a cut-away view of the antenna; and view C is a simplified diagram of the antenna.

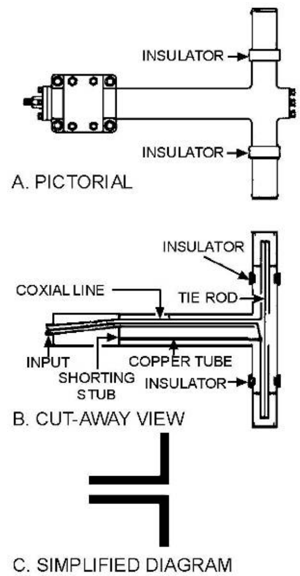

Figure 1-24.—Antenna.

Radio Waves

An energy wave generated by a transmitter is called a RADIO WAVE. The radio wave radiated into space by the transmitting antenna is a very complex form of energy containing both electric and magnetic fields. Because of this combination of fields, radio waves are also referred to as ELECTROMAGNETIC RADIATION. This discussion will explain the Earth's atmosphere and its effect on radio waves.

NOTE: The term radio wave is not limited to communications equipment alone. The term applies to all equipment that generates signals in the form of electromagnetic energy.

Components of Radio Waves

The basic shape of the wave generated by a transmitter is that of a sine wave. The wave radiated out into space, however, may or may not retain the characteristics of the sine wave.

A sine wave can be one cycle or many cycles. Recall from chapter 1 that the number of cycles of a sine wave that are completed in 1 second is known as the frequency of the sine wave. For example, 60 cycles of ordinary house current occur each second, so house current is said to have a frequency of 60 cycles per second or 60 hertz.

The frequencies falling between 3000 hertz (3 kHz) and 300,000,000,000 hertz (300 GHz) are called RADIO FREQUENCIES (abbreviated rf) since they are commonly used in radio communications. This part of the radio frequency spectrum is divided into bands, each band being 10 times higher in frequency than the one immediately below it. This arrangement serves as a convenient way to remember the range of each band. The rf bands are shown in table 1-1. The usable radio-frequency range is roughly 10 kilohertz to 100 gigahertz.

Table 1-1.—Radio Frequency Bands

DESCRIPTION	ABBREVIATION	FREQUENCY
Very low	VLF	3 to 30 KHz
Low	LF	30 to 300 KHz
Medium	MF	300 to 3000 KHz
High	HF	3 to 30 MHz
Very high	VHF	30 to 300 MHz
Ultrahigh	UHF	300 to 3000 MHz
Super high	SHF	3 to 30 GHz
Extremely high	EHF	30 to 300 GHz

The PERIOD of a radio wave is simply the amount of time required for the completion of one full cycle. If a sine wave has a frequency of 2 hertz, each cycle has a duration, or period, of one-half second. If the frequency is 10 hertz, the period of each cycle is one-tenth of a second. Since the frequency of a radio wave is the number of cycles that are completed in one second, you should be able to see that as the frequency of a radio wave increases, its period decreases.

A wavelength is the space occupied by one full cycle of a radio wave at any given instant. Wavelengths are expressed in meters (1 meter is equal to 3.28 feet). You need to have a good understanding of frequency and wavelength to be able to select the proper antenna(s) for use in successful communications.

The velocity (or speed) of a radio wave radiated into free space by a transmitting antenna is equal to the speed of light–186,000 miles per second or 300,000,000 meters per second. Because of various factors, such as barometric pressure, humidity, molecular content, etc., radio waves travel inside the Earth's atmosphere at a speed slightly less than the speed of light. Normally, in discussions of the velocity of radio waves, the velocity referred to is the speed at which radio waves travel in free space.

The frequency of a radio wave has nothing to do with its velocity. A 5-megahertz wave travels through space at the same velocity as a 10-megahertz wave. However, the velocity of radio waves is an important factor in making wavelength-to-frequency conversions, the subject of our next discussion.

☑**Learning Check**

1. What is the term used to describe the basic frequency of a radio wave?

Wavelength-to-Frequency Conversions

Radio waves are often referred to by their wavelength in meters rather than by frequency. For example, most people have heard commercial radio stations make announcements similar to the following: "Station WXYZ operating on 240 meters..." To tune receiving equipment that is calibrated by frequency to such a station, you must first convert the designated wavelength to its equivalent frequency.

As discussed earlier, a radio wave travels 300,000,000 meters a second (speed of light); therefore, a radio wave of 1 hertz would have traveled a distance (or wavelength) of 300,000,000 meters. Obviously then, if the frequency of the wave is increased to 2 hertz, the wavelength will be cut in half to 150,000,000 meters. This illustrates the principle that the HIGHER THE FREQUENCY, the SHORTER THE WAVELENGTH.

Wavelength-to-frequency conversions of radio waves are really quite simple because wavelength and frequency are reciprocals: Either one divided into the velocity of a radio wave yields the other. Remember, the formula for wavelength is:

$$\lambda = \frac{v}{f} \quad \text{or} \quad f = \frac{v}{\lambda}$$

Where:

λ = wavelength in meters

v = velocity of radio wave (speed of light)

f = frequency of radio wave (in Hz, kHz or Mhz)

The wavelength in meters divided into 300,000,000 yields the frequency of a radio wave in hertz. Likewise, the wavelength divided into 300,000 yields the frequency of a radio wave in kilohertz, and the wavelength divided into 300 yields the frequency in megahertz.

Now, let us apply the formula to determine the frequency to which the receiving equipment must be tuned to receive station WXYZ operating on 240 meters. Radio wave frequencies are normally expressed in kilohertz or megahertz.

To find the frequency in hertz, use the formula:

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

Given:

v = 300,000,000 meters per second

λ = 240 meters

Solution:

$$f = \frac{300{,}000{,}000 \text{ meters per second}}{240 \text{ meters}}$$

$$f = 1{,}250{,}000 \text{ Hz}$$

To find the frequency in kilohertz, use the formula:

$$f_{[\mathrm{kHz}]} = \frac{300{,}000}{\lambda}$$

Given:

λ = 240 meters

Solution:

$$f_{[\mathrm{kHz}]} = \frac{300{,}000}{240 \text{ meters}}$$

$$f = 1250\mathrm{kHz}$$

To find the frequency in megahertz, use the formula:

$$f_{[\mathrm{MHz}]} = \frac{300}{\lambda}$$

Given:

λ = 240 meters

Solution:

$$f_{[\mathrm{MHz}]} = \frac{300}{240 \text{ meters}}$$

$$f = 1.25\mathrm{MHz}$$

☑**Learning Check**

2. It is known that WWV operates on a frequency of 10 megahertz. What is the wavelength of WWV?

3. A station is known to operate at 60-meters. What is the frequency of the unknown station?

Polarization

For maximum absorption of energy from the electromagnetic fields, the receiving antenna must be located in the plane of polarization. This places the conductor of the antenna at right angles to the magnetic lines of force moving through the antenna and parallel to the electric lines, causing maximum induction.

Normally, the plane of polarization of a radio wave is the plane in which the E field propagates with respect to the Earth. If the E field component of the radiated wave travels in a plane perpendicular to the Earth's surface (vertical), the radiation is said to be VERTICALLY POLARIZED, as shown in figure 1-4, view A. If the E field propagates in a plane parallel to the Earth's surface (horizontal), the radiation is said to be HORIZONTALLY POLARIZED, as shown in view B.

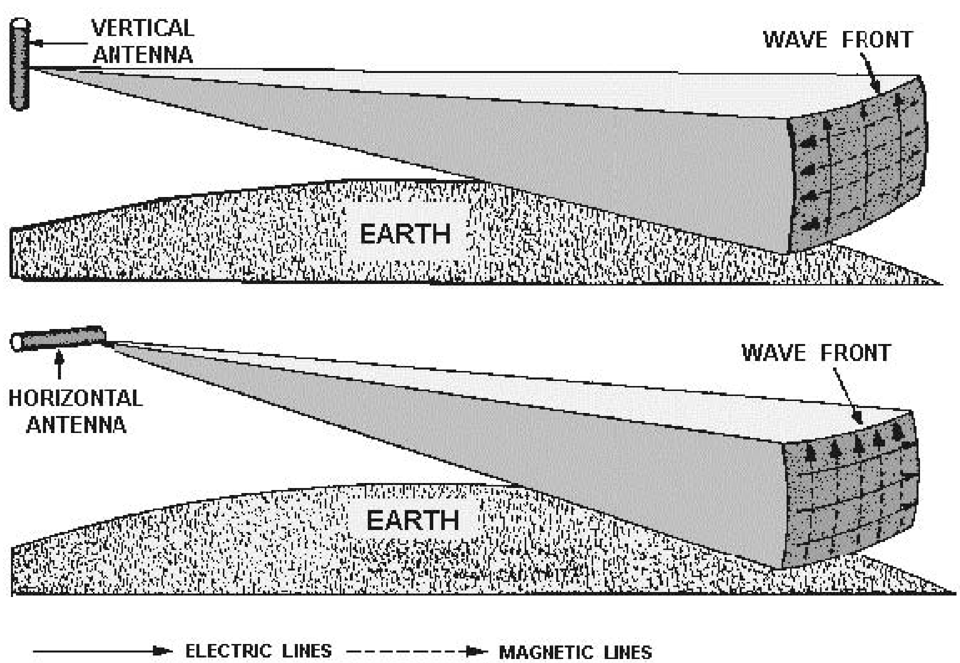

Figure 1-4 Polarization.

Atmospheric Propagation

Within the atmosphere, radio waves can be reflected, refracted, and diffracted like light and heat waves.

Reflection

Radio waves may be reflected from various substances or objects they meet during travel between the transmitting and receiving sites. The amount of reflection depends on the reflecting material. Smooth metal surfaces of good electrical conductivity are efficient reflectors of radio waves. The surface of the Earth itself is a fairly good reflector. The radio wave is not reflected from a single point on the reflector but rather from an area on its surface. The size of the area required for reflection to take place depends on the wavelength of the radio wave and the angle at which the wave strikes the reflecting substance.

When radio waves are reflected from flat surfaces, a phase shift in the alternations of the wave occurs. Figure 1-5 shows two radio waves being reflected from the Earth's surface. Radio waves that keep their phase relationships after reflection normally produce a stronger signal at the receiving site. Those that are received out of phase produce a weak or fading signal. The shifting in the phase relationships of reflected radio waves is one of the major reasons for fading. Fading will be discussed in more detail later in this chapter.

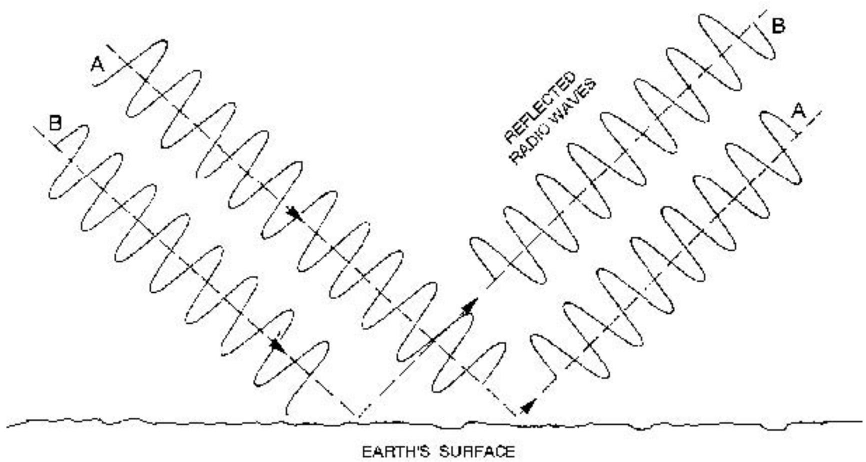

Figure 1-5.—Phase shift of reflected radio waves.

Refraction

Another phenomenon common to most radio waves is the bending of the waves as they move from one medium into another in which the velocity of propagation is different. This bending of the waves is called refraction. For example, suppose you are driving down a smoothly paved road at a constant speed and suddenly one wheel goes off onto the soft shoulder. The car tends to veer off to one side. The change of medium, from hard surface to soft shoulder, causes a change in speed or velocity. The tendency is for the car to change direction. This same principle applies to radio waves as changes occur in the medium through which they are passing. As an example, the radio wave shown in figure 1-6 is traveling through the Earth's atmosphere at a constant speed. As the wave enters the dense layer of electrically charged ions, the part of the wave that enters the new medium first travels faster than the parts of the wave that have not yet entered the new medium. This abrupt increase in velocity of the upper part of the wave causes the wave to bend back toward the Earth. This bending, or change of direction, is always toward the medium that has the lower velocity of propagation.

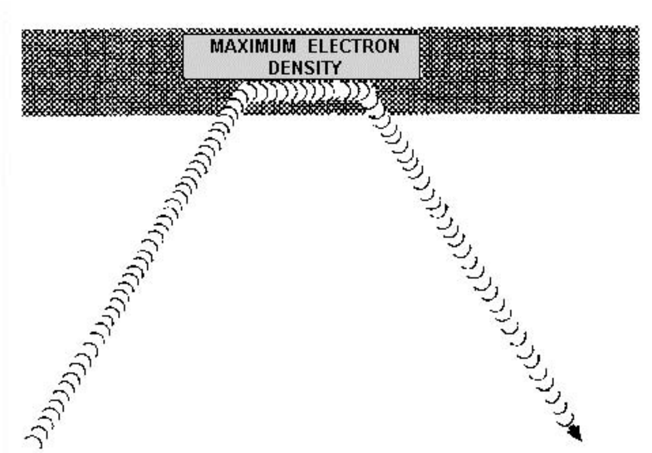

Figure 1-6.—Radio wave refraction.

Radio waves passing through the atmosphere are affected by certain factors, such as temperature, pressure, humidity, and density. These factors can cause the radio waves to be refracted. This effect will be discussed in greater detail later in this chapter.

Diffraction

A radio wave that meets an obstacle has a natural tendency to bend around the obstacle as illustrated in figure 1-7. The bending, called diffraction, results in a change of direction of part of the wave energy from the normal line-of-sight path. This change makes it possible to receive energy around the edges of an obstacle as shown in view A or at some distances below the highest point of an obstruction, as shown in view B. Although diffracted rf energy usually is weak, it can still be detected by a suitable receiver. The principal effect of diffraction extends the radio range beyond the visible horizon. In certain cases, by using high power and very low frequencies, radio waves can be made to encircle the Earth by diffraction.

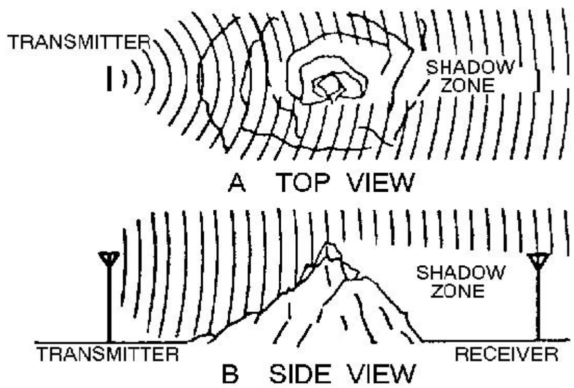

Figure 1-7.—Diffraction around an object.

☑**Learning Check**

4. What is one of the major reasons for the fading of radio waves which have been reflected from a surface?

The Effect of the Earth's Atmosphere on Radio Waves

This discussion of electromagnetic wave propagation is concerned mainly with the properties and effects of the medium located between the transmitting antenna and the receiving antenna. While radio waves traveling in free space have little outside influence affecting them, radio waves traveling within the Earth's atmosphere are affected by varying conditions. The influence exerted on radio waves by the Earth's atmosphere adds many new factors to complicate what at first seems to be a relatively simple problem. These complications are because of a lack of uniformity within the Earth's atmosphere. Atmospheric conditions vary with changes in height, geographical location, and even with changes in time (day, night, season, year). A knowledge of the composition of the Earth's atmosphere is extremely important for understanding wave propagation.

The Earth's atmosphere is divided into three separate regions, or layers. They are the TROPOSPHERE, the STRATOSPHERE, and the IONOSPHERE. The layers of the atmosphere are illustrated in figure1-8.

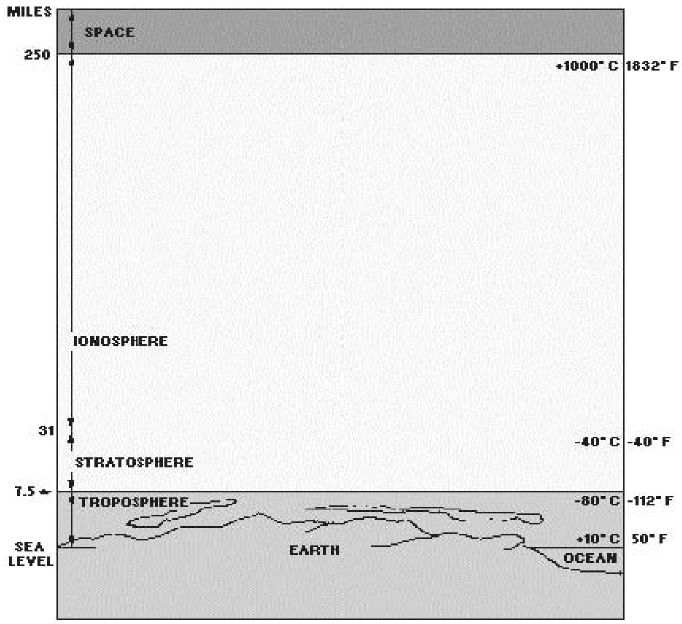

Figure 1-8—Layers of the earth's atmosphere.

Troposphere

The troposphere is the portion of the Earth's atmosphere that extends from the surface of the Earth to a height of about 3.7 miles (6 km) at the North Pole or the South Pole and 11.2 miles (18 km) at the equator. Virtually all weather phenomena take place in the troposphere. The temperature in this region decreases rapidly with altitude, clouds form, and there may be much turbulence because of variations in temperature, density, and pressure. These conditions have a great effect on the propagation of radio waves, which will be explained later in this chapter.

Stratosphere

The stratosphere is located between the troposphere and the ionosphere. The temperature throughout this region is considered to be almost constant and there is little water vapor present. The stratosphere has relatively little effect on radio waves because it is a relatively calm region with little or no temperature changes.

Ionosphere

The ionosphere extends upward from about 31.1 miles (50 km) to a height of about 250 miles (402 km). It contains four cloud-like layers of electrically charged ions, which enable radio waves to be propagated to great distances around the Earth. This is the most important region of the atmosphere for long distance point-to-point communications.

☑**Learning Check**

5. What are the three layers of the atmosphere?

6. Which layer of the atmosphere has relatively little effect on radio waves?

Radio Wave Transmission

There are two principal ways in which electromagnetic (radio) energy travels from a transmitting antenna to a receiving antenna. One way is by GROUND WAVES and the other is by SKY WAVES. Ground waves are radio waves that travel near the surface of the Earth (surface and space waves). Sky waves are radio waves that are reflected back to Earth from the ionosphere. (See figure 1-9.)

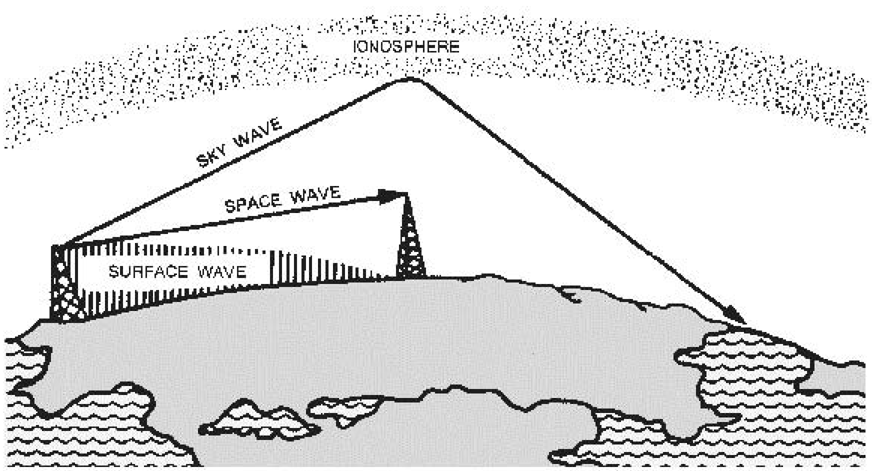

Figure 1-9.—Ground waves and sky waves.

Ground Waves

The ground wave is actually composed of two separate component waves. These are known as the SURFACE WAVE and the SPACE WAVE (fig. 1-9). The determining factor in whether a ground wave component is classified as a space wave or a surface wave is simple. A surface wave travels along the surface of the Earth. A space wave travels over the surface.

SURFACE WAVE.—The surface wave reaches the receiving site by traveling along the surface of the ground as shown in figure 1-10. A surface wave can follow the contours of the Earth because of the process of diffraction. When a surface wave meets an object and the dimensions of the object do not exceed its wavelength, the wave tends to curve or bend around the object. The smaller the object, the more pronounced the diffractive action will be.

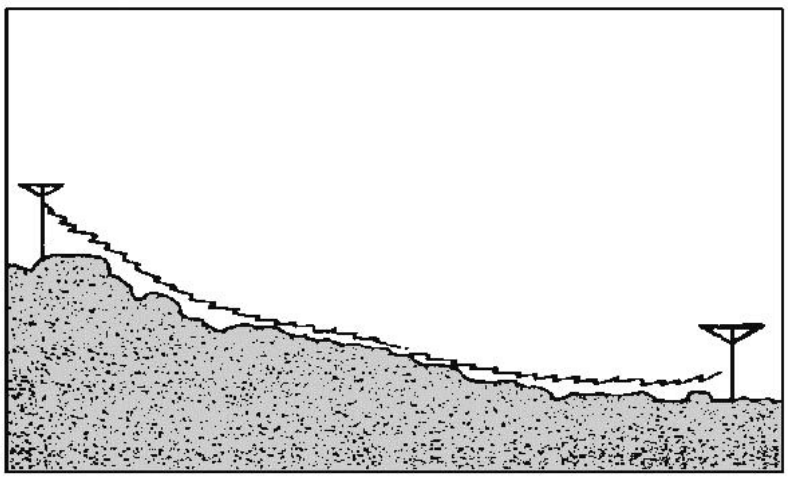

Figure 1-10.—Surface wave propagation.

As a surface wave passes over the ground, the wave induces a voltage in the Earth. The induced voltage takes energy away from the surface wave, thereby weakening, or attenuating, the wave as it moves away from the transmitting antenna. To reduce the attenuation, the amount of induced voltage must be reduced. This is done by using vertically polarized waves that minimize the extent to which the electric field of the wave is in contact with the Earth. When a surface wave is horizontally polarized, the electric field of the wave is parallel with the surface of the Earth and, therefore, is constantly in contact with it. The wave is then completely attenuated within a short distance from the transmitting site. On the other hand, when the surface wave is vertically polarized, the electric field is vertical to the Earth and merely dips into and out of the Earth's surface. For this reason, vertical polarization is vastly superior to horizontal polarization for surface wave propagation.

The attenuation that a surface wave undergoes because of induced voltage also depends on the electrical properties of the terrain over which the wave travels. The best type of surface is one that has good electrical conductivity. The better the conductivity, the less the attenuation. Table 1-2 gives the relative conductivity of various surfaces of the Earth.

Table 1-2.—Surface Conductivity

Surface	Relative Conductivity
Sea water	Good
Flat, loamy soil	Fair
Large bodies of fresh water	Fair
Rocky terrain	Poor
Desert	Poor
Jungle	Unusable

Another major factor in the attenuation of surface waves is frequency. Recall from earlier discussions on wavelength that the higher the frequency of a radio wave, the shorter its wavelength will be. These high frequencies, with their shorter wavelengths, are not normally diffracted but are absorbed by the Earth at points relatively close to the transmitting site. You can assume, therefore, that as the frequency of a surface wave is increased, the more rapidly the surface wave will be absorbed, or attenuated, by the Earth. Because of this loss by attenuation, the surface wave is impractical for long-distance transmissions at frequencies above 2 megahertz. On the other hand, when the frequency of a surface wave is low enough to have a very long wavelength, the Earth appears to be very small, and diffraction is sufficient for propagation well beyond the horizon. In fact, by lowering the transmitting frequency into the very low frequency (vlf) range and using very high-powered transmitters, the surface wave can be propagated great distances.

SPACE WAVE.—The space wave follows two distinct paths from the transmitting antenna to the receiving antenna—one through the air directly to the receiving antenna, the other reflected from the ground to the receiving antenna. This is illustrated in figure 1-11. The primary path of the space wave is directly from the transmitting antenna to the receiving antenna. So, the receiving antenna must be located within the radio horizon of the transmitting antenna. Because space waves are refracted slightly, even when propagated through the troposphere, the radio horizon is actually about one-third farther than the line-of-sight or natural horizon.

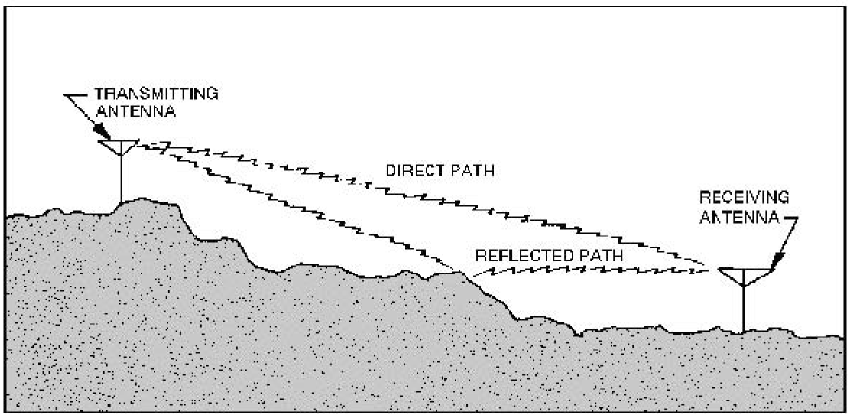

Figure 1-11.—Space wave propagation.

Although space waves suffer little ground attenuation, they nevertheless are susceptible to fading. This is because space waves actually follow two paths of different lengths (direct path and ground reflected path) to the receiving site and, therefore, may arrive in or out of phase. If these two component waves are received in phase, the result is a reinforced or stronger signal. Likewise, if they are received out of phase, they tend to cancel one another, which results in a weak or fading signal.

☑Learning Check

7. What is the determining factor in classifying whether a radio wave is a ground wave or a space wave?

8. What is the best type of surface or terrain to use for radio wave transmission?

9. What is the primary difference between the radio horizon and the natural horizon?

10. What three factors must be considered in the transmission of a surface wave to reduce attenuation?

Sky Wave

The sky wave, often called the ionospheric wave, is radiated in an upward direction and returned to Earth at some distant location because of refraction from the ionosphere. This form of propagation is relatively unaffected by the Earth's surface and can propagate signals over great distances. Usually the high frequency (hf) band is used for sky wave propagation.

Refraction in the Ionosphere

When a radio wave is transmitted into an ionized layer, refraction, or bending of the wave, occurs. As we discussed earlier, refraction is caused by an abrupt change in the velocity of the upper part of a radio wave as it strikes or enters a new medium. The amount of refraction that occurs depends on three main factors: (1) the density of ionization of the layer, (2) the frequency of the radio wave, and (3) the angle at which the wave enters the layer.

Skip Distance/Skip Zone

In figure 1-12, note the relationship between the sky wave skip distance, the skip zone, and the ground wave coverage. The SKIP DISTANCE is the distance from the transmitter to the point where the sky wave is first returned to Earth. The size of the skip distance depends on the frequency of the wave, the angle of incidence, and the degree of ionization present.

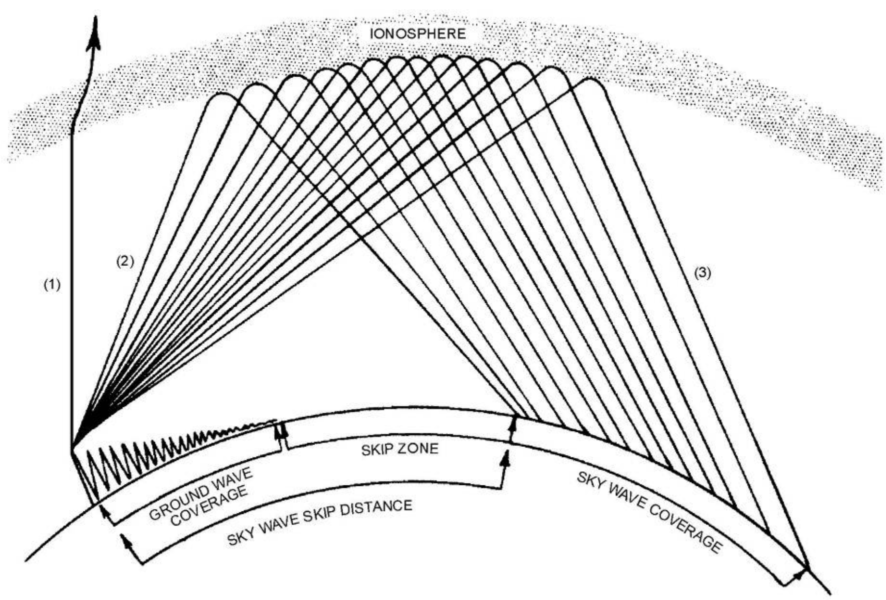

Figure 1-12.—Relationship between skip zone, skip distance, and ground wave.

The SKIP ZONE is a zone of silence between the point where the ground wave becomes too weak for reception and the point where the sky wave is first returned to Earth. The size of the skip zone depends on the extent of the ground wave coverage and the skip distance. When the ground wave coverage is great enough or the skip distance is short enough that no zone of silence occurs, there is no skip zone.

Occasionally, the first sky wave will return to Earth within the range of the ground wave. If the sky wave and ground wave are nearly of equal intensity, the sky wave alternately reinforces and cancels the ground wave, causing severe fading. This is caused by the phase difference between the two waves, a result of the longer path traveled by the sky wave.

Fading

The most troublesome and frustrating problem in receiving radio signals is variations in signal strength, most commonly known as FADING. There are several conditions that can produce fading. When a radio wave is refracted by the ionosphere or reflected from the Earth's surface, random changes in the polarization of the wave may occur. Vertically and horizontally mounted receiving antennas are designed to receive vertically and horizontally polarized waves, respectively. Therefore, changes in polarization cause changes in the received signal level because of the inability of the antenna to receive polarization changes.

Fading also results from absorption of the rf energy in the ionosphere. Absorption fading occurs for a longer period than other types of fading, since absorption takes place slowly.

Usually, however, fading on ionospheric circuits is mainly a result of multipath propagation.

Multipath Fading

MULTIPATH is simply a term used to describe the multiple paths a radio wave may follow between transmitter and receiver. Such propagation paths include the ground wave, ionospheric refraction, reradiation by the ionospheric layers, reflection from the Earth's surface or from more than one ionospheric layer, etc. Figure 1-13 shows a few of the paths that a signal can travel between two sites in a typical circuit. One path, XYZ, is the basic ground wave. Another path, XEA, refracts the wave at the E layer and passes it on to the receiver at A. Still another path, XFZFA, results from a greater angle of incidence and two refractions from the F layer. At point Z, the received signal is a combination of the ground wave and the sky wave. These two signals having traveled different paths arrive at point Z at different times. Thus, the arriving waves may or may not be in phase with each other. Radio waves that are received in phase reinforce each other and produce a stronger signal at the receiving site. Conversely, those that are received out of phase produce a weak or fading signal. Small alternations in the transmission path may change the phase relationship of the two signals, causing periodic fading. This condition occurs at point A. At this point, the double-hop F layer signal may be in or out of phase with the signal arriving from the E layer.

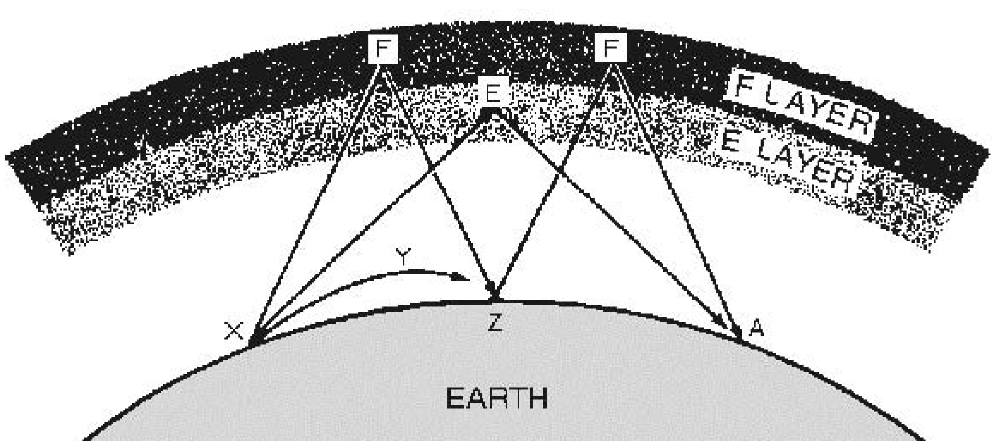

Figure 1-13.—Multipath transmission.

Multipath fading may be minimized by practices called SPACE DIVERSITY and FREQUENCY DIVERSITY. In space diversity, two or more receiving antennas are spaced some distance apart. Fading does not occur simultaneously at both antennas; therefore, enough output is almost always available from one of the antennas to provide a useful signal. In frequency diversity, two transmitters and two receivers are used, each pair tuned to a different frequency, with the same information being transmitted simultaneously over both frequencies. One of the two receivers will almost always provide a useful signal.

☑**Learning Check**

11. What is the skip zone of a radio wave?

12. Where does the greatest amount of ionospheric absorption occur in the ionosphere?

13. What is meant by the term "multipath"?

Transmission Losses

All radio waves propagated over ionospheric paths undergo energy losses before arriving at the receiving site. As we discussed earlier, absorption in the ionosphere and lower atmospheric levels account for a large part of these energy losses. There are two other types of losses that also significantly affect the ionospheric propagation of radio waves. These losses are known as ground reflection loss and free space loss. The combined effects of absorption, ground reflection loss, and free space loss account for most of the energy losses of radio transmissions propagated by the ionosphere.

Ground Reflection Loss

When propagation is accomplished via multihop refraction, rf energy is lost each time the radio wave is reflected from the Earth's surface. The amount of energy lost depends on the frequency of the wave, the angle of incidence, ground irregularities, and the electrical conductivity of the point of reflection.

Free Space Loss

Normally, the major loss of energy is because of the spreading out of the wavefront as it travels away from the transmitter. As the distance increases, the area of the wavefront spreads out, much like the beam of a flashlight. This means the amount of energy contained within any unit of area on the wavefront will decrease as distance increases. By the time the energy arrives at the receiving antenna, the wavefront is so spread out that the receiving antenna extends into only a very small fraction of the wavefront. This is illustrated in figure 1-14.

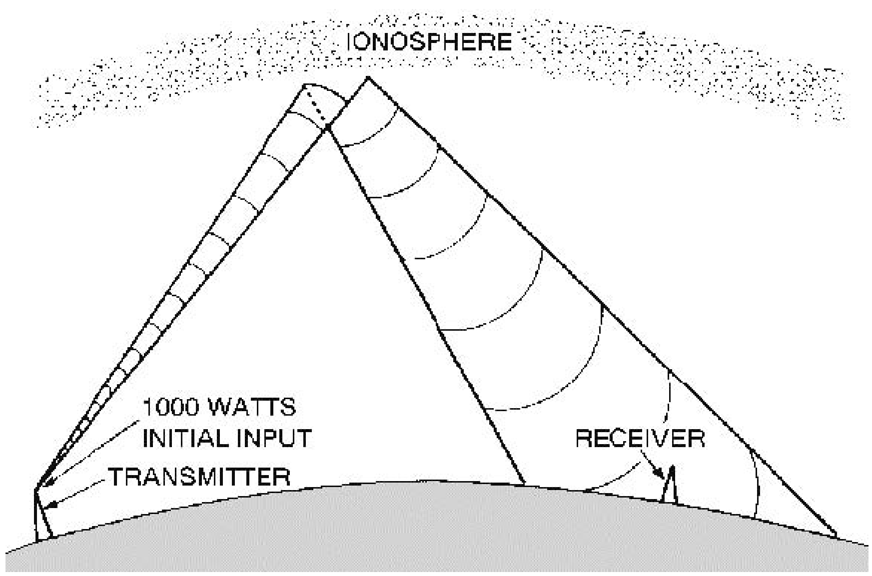

Figure 1-14.—Free space loss principle.

Electromagnetic Interference (EMI)

The transmission losses just discussed are not the only factors that interfere with communications. An additional factor that can interfere with radio communications is the presence of ELECTROMAGNETIC INTERFERENCE (EMI). This interference can result in annoying or impossible operating conditions. Sources of emi are both man-made and natural.

Man-Made Interference

Man-made interference may come from several sources. Some of these sources, such as oscillators, communications transmitters, and radio transmitters, may be specifically designed to generate radio frequency energy. Some electrical devices also generate radio frequency energy, although they are not specifically designed for this purpose. Examples are ignition systems, generators, motors, switches, relays, and voltage regulators. The intensity of man-made interference may vary throughout the day and drop off to a low level at night when many of these sources are not being used. Man-made interference may be a critical limiting factor at radio receiving sites located near industrial areas.

Natural Interference

Natural interference refers to the static that you often hear when listening to a radio. This interference is generated by natural phenomena, such as thunderstorms, snowstorms, cosmic sources, and the sun. The energy released by these sources is transmitted to the receiving site in roughly the same manner as radio waves. As a result, when ionospheric conditions are favorable for the long distance propagation of radio waves, they are likewise favorable for the propagation of natural interference. Natural interference is very erratic, particularly in the hf band, but generally will decrease as the operating frequency is increased and wider bandwidths are used. There is little natural interference above 30 megahertz.

Control of EMI

Electromagnetic interference can be reduced or eliminated by using various suppression techniques. The amount of emi that is produced by a radio transmitter can be controlled by cutting transmitting antennas to the correct frequency, limiting bandwidth, and using electronic filtering networks and metallic shielding.

Radiated emi during transmission can be controlled by the physical separation of the transmitting and receiving antennas, the use of directional antennas, and limiting antenna bandwidth.

☑**Learning Check**

14. What are the two main sources of emi with which radio waves must compete?

15. Thunderstorms, snowstorms, cosmic sources, the sun, etc., are a few examples of emi sources. What type of emi comes from these sources?

16. Motors, switches, voltage regulators, generators, etc., are a few examples of emi sources. What type of emi comes from these sources?

17. What are three ways of controlling the amount of transmitter-generated emi?

18. What are three ways of controlling radiated emi during transmission?

Weather versus Propagation

Weather is an additional factor that affects the propagation of radio waves. In this section, we will explain how and to what extent the various weather phenomena affect wave propagation.

Wind, air temperature, and water content of the atmosphere can combine in many ways. Certain combinations can cause radio signals to be heard hundreds of miles beyond the ordinary range of radio communications. Conversely, a different combination of factors can cause such attenuation of the signal that it may not be heard even over a normally satisfactory path. Unfortunately, there are no hard and fast rules on the effects of weather on radio transmissions since the weather is extremely complex and subject to frequent change. We will, therefore, limit our discussion on the effects of weather on radio waves to general terms.

Precipitation Attenuation

Calculating the effect of weather on radio wave propagation would be comparatively simple if there were no water or water vapor in the atmosphere. However, some form of water (vapor, liquid, or solid) is always present and must be considered in all calculations. Before we begin discussing the specific effects that individual forms of precipitation (rain, snow, fog) have on radio waves, you should understand that attenuation because of precipitation is generally proportionate to the frequency and wavelength of the radio wave. For example, rain has a pronounced effect on waves at microwave frequencies. However, rain hardly affects waves with long wavelengths (hf range and below). You can assume, then, that as the wavelength becomes shorter with increases in frequency, precipitation has an increasingly important attenuation effect on radio waves. Conversely, you can assume that as the wavelength becomes longer with decreases in frequency, precipitation has little attenuation effect.

Rain

Attenuation because of raindrops is greater than attenuation because of other forms of precipitation. Attenuation may be caused by absorption, in which the raindrop, acting as a poor dielectric, absorbs power from the radio wave and dissipates the power by heat loss or by scattering (fig. 1-15). Raindrops cause greater attenuation by scattering than by absorption at frequencies above 100 megahertz. At frequencies above 6 gigahertz, attenuation by raindrop scatter is even greater.

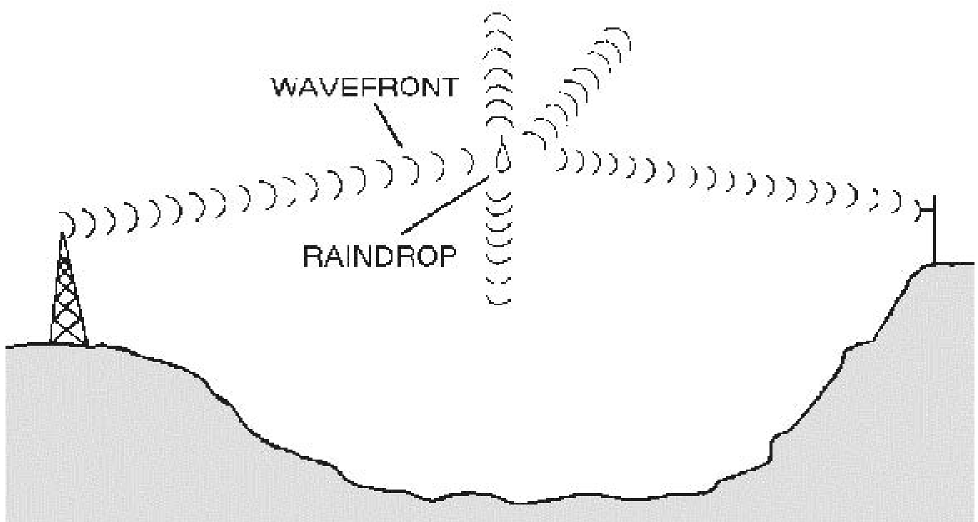

Figure1-15.—Rf energy losses from scattering.

Fog

In the discussion of attenuation, fog may be considered as another form of rain. Since fog remains suspended in the atmosphere, the attenuation is determined by the quantity of water per unit volume and by the size of the droplets. Attenuation because of fog is of minor importance at frequencies lower than 2 gigahertz. However, fog can cause serious attenuation by absorption, at frequencies above 2 gigahertz.

Snow

The scattering effect because of snow is difficult to compute because of irregular sizes and shapes of the flakes. While information on the attenuating effect of snow is limited, scientists assume that attenuation from snow is less than from rain falling at an equal rate. This assumption is borne out by the fact that the density of rain is eight times the density of snow. As a result, rain falling at 1 inch per hour would have more water per cubic inch than snow falling at the same rate.

Hail

Attenuation by hail is determined by the size of the stones and their density. Attenuation of radio waves by scattering because of hailstones is considerably less than by rain.

Temperature Inversion

Under normal atmospheric conditions, the warmest air is found near the surface of the Earth. The air gradually becomes cooler as altitude increases. At times, however, an unusual situation develops in which layers of warm air are formed above layers of cool air. This condition is known as TEMPERATURE INVERSION. These temperature inversions cause channels, or ducts, of cool air to be sandwiched between the surface of the Earth and a layer of warm air, or between two layers of warm air.

If a transmitting antenna extends into such a duct of cool air, or if the radio wave enters the duct at a very low angle of incidence, vhf and uhf transmissions may be propagated far beyond normal line-of-sight distances. When ducts are present as a result of temperature inversions, good reception of vhf and uhf television signals from a station located hundreds of miles away is not unusual. These long distances are possible because of the different densities and refractive qualities of warm and cool air. The sudden change in density when a radio wave enters the warm air above a duct causes the wave to be refracted back toward Earth. When the wave strikes the Earth or a warm layer below the duct, it is again reflected or refracted upward and proceeds on through the duct with a multiple-hop type of action. An example of the propagation of radio waves by ducting is shown in figure 1-16.

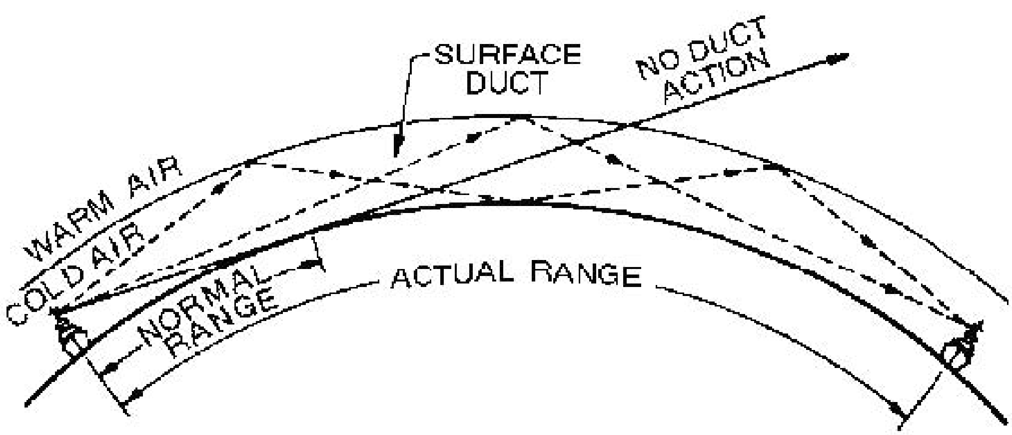

Figure 1-16.—Duct effect caused by temperature inversion.

☑**Learning Check**

19. How do raindrops affect radio waves?

20. How does fog affect radio waves at frequencies above 2 gigahertz?

21. How is the term "temperature inversion" used when referring to radio waves?

22. How does temperature inversion affect radio transmission?

Tropospheric Propagation

As the lowest region of the Earth's atmosphere, the troposphere extends from the Earth's surface to a height of slightly over 7 miles. Virtually all weather phenomena occur in this region. Generally, the troposphere is characterized by a steady decrease in both temperature and pressure as height is increased. However, the many changes in weather phenomena cause variations in humidity and an uneven heating of the Earth's surface. As a result, the air in the troposphere is in constant motion. This motion causes small turbulences, or eddies, to be formed, as shown by the bouncing of aircraft entering turbulent areas of the atmosphere. These turbulences are most intense near the Earth's surface and gradually diminish with height. They have a refractive quality that permits the refracting or scattering of radio waves with short wavelengths. This scattering provides enhanced communications at higher frequencies.

Recall that in the relationship between frequency and wavelength, wavelength decreases as frequency increases and vice versa. Radio waves of frequencies below 30 megahertz normally have wavelengths longer than the size of weather turbulences. These radio waves are, therefore, affected very little by the turbulences. On the other hand, as the frequency increases into the vhf range and above, the wavelengths decrease in size, to the point that they become subject to tropospheric scattering. The usable frequency range for tropospheric scattering is from about 100 megahertz to 10 gigahertz.

☑**Learning Check**

23. In what layer of the atmosphere does virtually all weather phenomena occur?

CHAPTER 2: TRANSMISSION LINES

Learning Objectives

Upon completion of this chapter, you will be able to:

- State what a transmission line is and how transmission lines are used; and
- Describe the five types of transmission lines.

Introduction to Transmission Lines

A TRANSMISSION LINE is a device designed to guide electrical energy from one point to another. It is used, for example, to transfer the output rf energy of a transmitter to an antenna. This energy will not travel through normal electrical wire without great losses. Although the antenna can be connected directly to the transmitter, the antenna is usually located some distance away from the transmitter. A transmission line is used to connect the transmitter and the antenna.

The transmission line has a single purpose for both the transmitter and the antenna. This purpose is to transfer the energy output of the transmitter to the antenna with the least possible power loss. How well this is done depends on the special physical and electrical characteristics (impedance and resistance) of the transmission line.

Terminology

All transmission lines have two ends (see figure 1-17). The end of a two-wire transmission line connected to a source is ordinarily called the INPUT END or the GENERATOR END. Other names given to this end are TRANSMITTER END, SENDING END, and SOURCE. The other end of the line is called the OUTPUT END or RECEIVING END. Other names given to the output end are LOAD END and SINK.

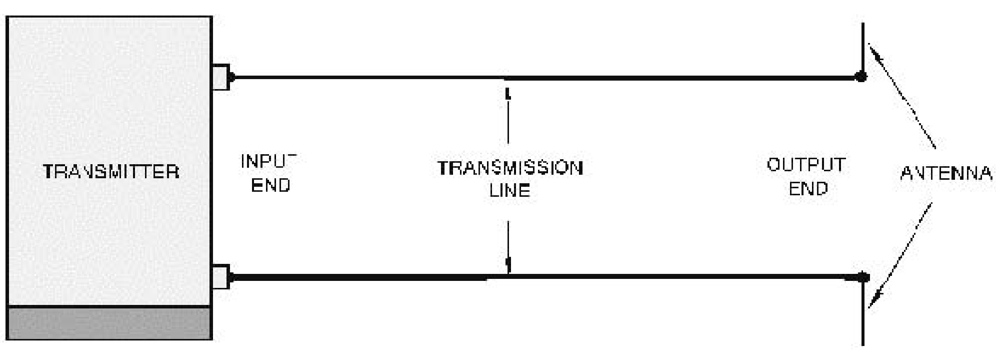

Figure 1-17.—Basic transmission line.

Types of Transmission Mediums

Many different types of TRANSMISSION MEDIUMS are used depending on the electronic application. Each medium (line or wave guide) has a certain characteristic impedance value, current-carrying capacity, and physical shape and is designed to meet a particular requirement.

The five types of transmission mediums that we will discuss in this chapter include PARALLEL-LINE, TWISTED PAIR, SHIELDED PAIR, COAXIAL LINE, and WAVEGUIDES. The use of a particular line depends, among other things, on the applied frequency, the power-handling capabilities, and the type of installation.

NOTE: In the following paragraphs, we will mention LOSSES several times. We will discuss these losses more thoroughly under "LOSSES IN TRANSMISSION LINES."

Two-Wire Open Line

One type of parallel line is the TWO-WIRE OPEN LINE illustrated in figure 1-18. This line consists of two wires that are generally spaced from 2 to 6 inches apart by insulating spacers. This type of line is most often used for power lines, rural telephone lines, and telegraph lines. It is sometimes used as a transmission line between a transmitter and an antenna or between an antenna and a receiver. An advantage of this type of line is its simple construction. The principal disadvantages of this type of line are the high radiation losses and electrical noise pickup because of the lack of shielding. Radiation losses are produced by the changing fields created by the changing current in each conductor.

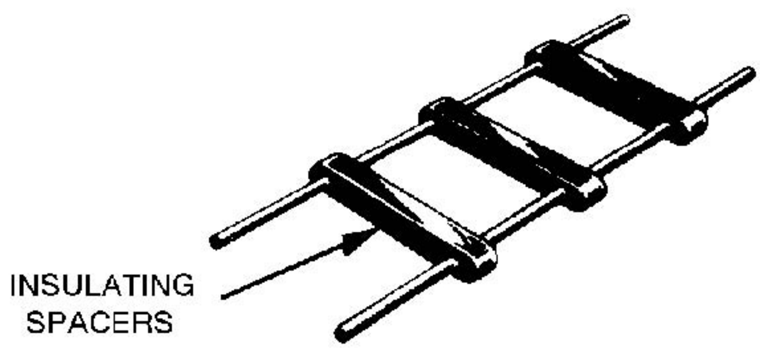

Figure 1-18.—Parallel two-wire line.

Another type of parallel line is the TWO-WIRE RIBBON (TWIN LEAD) illustrated in figure 1-19. This type of transmission line is commonly used to connect a television receiving antenna to a home television set. This line is essentially the same as the two-wire open line except that uniform spacing is assured by embedding the two wires in a low-loss dielectric, usually polyethylene. Since the wires are embedded in the thin ribbon of polyethylene, the dielectric space is partly air and partly polyethylene.

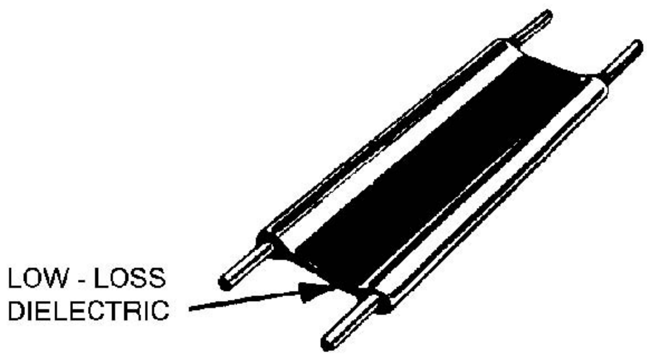

Figure 1-19.—Two-wire ribbon type line.

Twisted Pair

The TWISTED PAIR transmission line is illustrated in figure 1-20. As the name implies, the line consists of two insulated wires twisted together to form a flexible line without the use of spacers. It is not used for transmitting high frequency because of the high dielectric losses that occur in the rubber insulation. When the line is wet, the losses increase greatly.

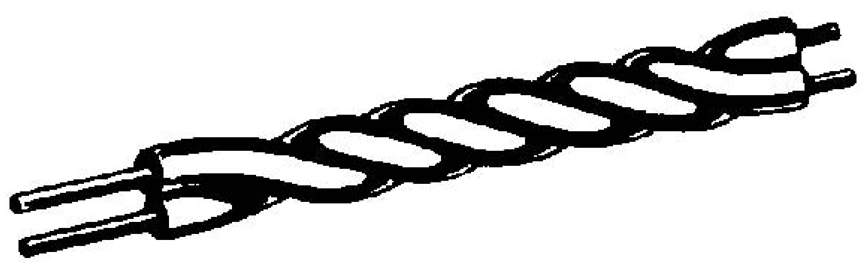

Figure 1-20.—Twisted pair.

Shielded Pair

The SHIELDED PAIR, shown in figure 1-21, consists of parallel conductors separated from each other and surrounded by a solid dielectric. The conductors are contained within a braided copper tubing that acts as an electrical shield. The assembly is covered with a rubber or flexible composition coating that protects the line from moisture and mechanical damage. Outwardly, it looks much like the power cord of a washing machine or refrigerator.

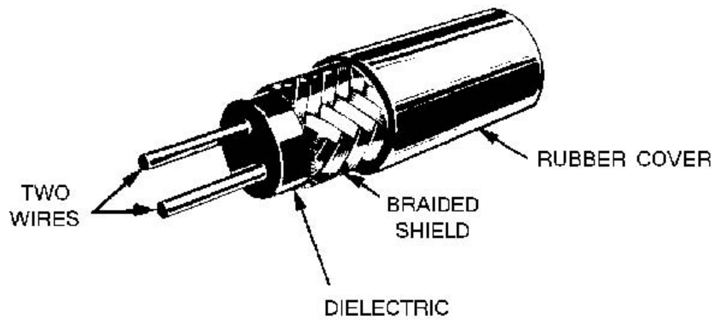

Figure 1-21.—Shielded pair.

The principal advantage of the shielded pair is that the conductors are balanced to ground; that is, the capacitance between the wires is uniform throughout the length of the line. This balance is due to the uniform spacing of the grounded shield that surrounds the wires along their entire length. The braided copper shield isolates the conductors from stray magnetic fields.

Coaxial Lines

There are two types of COAXIAL LINES, RIGID (AIR) COAXIAL LINE and FLEXIBLE (SOLID) COAXIAL LINE. The physical construction of both types is basically the same; that is, each contains two concentric conductors.

The rigid coaxial line consists of a central, insulated wire (inner conductor) mounted inside a tubular outer conductor. This line is shown in figure 1-22. In some applications, the inner conductor is also tubular. The inner conductor is insulated from the outer conductor by insulating spacers or beads at regular intervals. The spacers are made of Pyrex, polystyrene, or some other material that has good insulating characteristics and low dielectric losses at high frequencies.

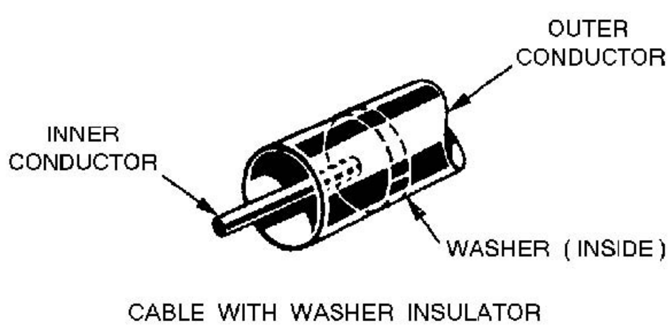

Figure 1-22.—Air coaxial line.

The chief advantage of the rigid line is its ability to minimize radiation losses. The electric and magnetic fields in a two-wire parallel line extend into space for relatively great distances and radiation losses occur. However, in a coaxial line no electric or magnetic fields extend outside of the outer conductor. The fields are confined to the space between the two conductors, resulting in a perfectly shielded coaxial line. Another advantage is that interference from other lines is reduced.

The rigid line has the following disadvantages: (1) it is expensive to construct; (2) it must be kept dry to prevent excessive leakage between the two conductors; and (3) although high-frequency losses are somewhat less than in previously mentioned lines, they are still excessive enough to limit the practical length of the line.

Leakage caused by the condensation of moisture is prevented in some rigid line applications by the use of an inert gas, such as nitrogen, helium, or argon. It is pumped into the dielectric space of the line at a pressure that can vary from 3 to 35 pounds per square inch. The inert gas is used to dry the line when it is first installed and pressure is maintained to ensure that no moisture enters the line.

Flexible coaxial lines (figure 1-23) are made with an inner conductor that consists of flexible wire insulated from the outer conductor by a solid, continuous insulating material. The outer conductor is made of metal braid, which gives the line flexibility. Early attempts at gaining flexibility involved using rubber insulators between the two conductors. However, the rubber insulators caused excessive losses at high frequencies.

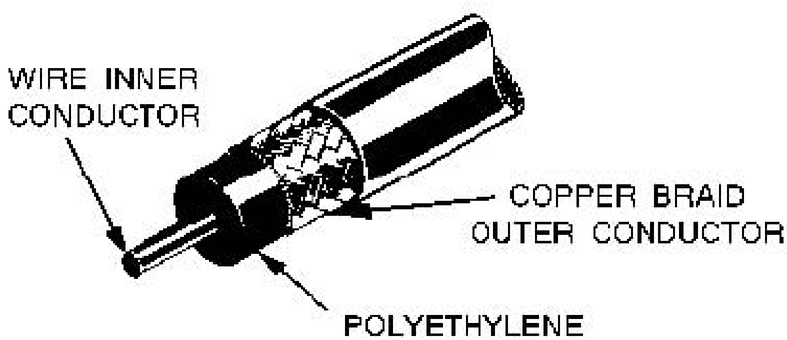

Figure 1-23.—Flexible coaxial line.

Because of the high-frequency losses associated with rubber insulators, polyethylene plastic was developed to replace rubber and eliminate these losses. Polyethylene plastic is a solid substance that remains flexible over a wide range of temperatures. It is unaffected by seawater, gasoline, oil, and most other liquids that may be found aboard ship. The use of polyethylene as an insulator results in greater high-frequency losses than the use of air as an insulator. However, these losses are still lower than the losses associated with most other solid dielectric materials.

☑**Learning Check**

24. List the five types of transmission lines in use today.

25. Name two of the three described uses of a two-wire open line.

26. What are the two primary disadvantages of a two-wire open line?

27. What type of transmission line is often used to connect a television set to its antenna?

28. What is the primary advantage of the shielded pair?

29. What are the two types of coaxial lines in use today?

30. What is the chief advantage of the air coaxial line?

31. List the three disadvantages of the air coaxial line.

CHAPTER 3: ANTENNAS

Learning Objectives

Upon completion of this chapter, you will be able to:

- State the basic principles of antenna radiation and list the parts of an antenna;
- Describe how electromagnetic energy is radiated from an antenna;
- Explain polarization, gain, and radiation resistance characteristics of an antenna;
- Describe the theory of operation of half- wave and quarter-wave antennas;
- List the various array antennas;
- Describe the directional array antennas presented and explain the basic operation of each; and
- Identify various special antennas presented, such as ground-plane, and corner-reflector; describe the operation of each.

Introduction

If you had been around in the early days of electronics, you would have considered an ANTENNA (AERIAL) to be little more than a piece of wire strung between two trees or upright poles. In those days, technicians assumed that longer antennas automatically provided better reception than shorter antennas. They also believed that a mysterious MEDIUM filled all space, and that an antenna used this medium to send and receive its energy. These two assumptions have since been discarded. Modern antennas have evolved to the point that highly directional, specially designed antennas are used to relay worldwide communications in space through the use of satellites and Earth station antennas (fig. 1-24). Present transmission theories are based on the assumption that space itself is the only medium necessary to propagate (transmit) radio energy.

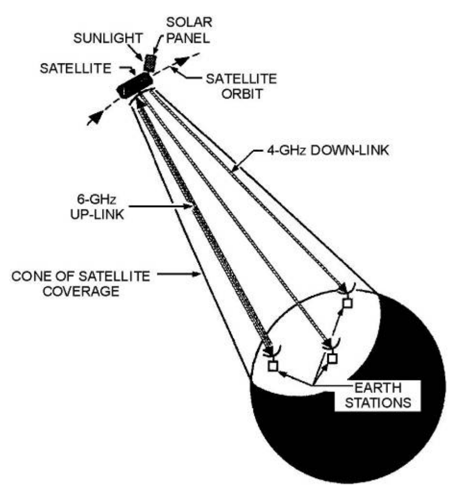

Figure 1-24.—Satellite/earth station communications system.

A tremendous amount of knowledge and information has been gained about the design of antennas and radio-wave propagation. Still, many old-time technicians will tell you that when it comes to designing the length of an antenna, the best procedure is to perform all calculations and try out the antenna. If it doesn't work right, use a cut-and-try method until it does. Fortunately, enough information has been collected over the last few decades that it is now possible to predict the behavior of antennas. This chapter will discuss and explain the basic design and operation of antennas.

Principles of Antenna Radiation

After an rf signal has been generated in a transmitter, some means must be used to radiate this signal through space to a receiver. The device that does this job is the antenna. The transmitter signal energy is sent into space by a TRANSMITTING ANTENNA; the rf signal is then picked up from space by a RECEIVING ANTENNA.

The rf energy is transmitted into space in the form of an electromagnetic field. As the traveling electromagnetic field arrives at the receiving antenna, a voltage is induced into the antenna (a conductor). The rf voltages induced into the receiving antenna are then passed into the receiver and converted back into the transmitted rf information.

The design of the antenna system is very important in a transmitting station. The antenna must be able to radiate efficiently so the power supplied by the transmitter is not wasted. An efficient transmitting antenna must have exact dimensions. The dimensions are determined by the transmitting frequencies. The dimensions of the receiving antenna are not critical for relatively low radio frequencies. However, as the frequency of the signal being received increases, the design and installation of the receiving antenna become more critical. An example of this is a television receiving antenna. If you raise it a few more inches from the ground or give a slight turn in direction, you can change a snowy blur into a clear picture.

The conventional antenna is a conductor, or system of conductors, that radiates or intercepts electromagnetic wave energy. An ideal antenna has a definite length and a uniform diameter, and is completely isolated in space. However, this ideal antenna is not realistic. Many factors make the design of an antenna for a communications system a more complex problem than you would expect. These factors include the height of the radiator above the earth, the conductivity of the earth below it, and the shape and dimensions of the antenna. All of these factors affect the radiated-field pattern of the antenna in space. Another problem in antenna design is that the radiation pattern of the antenna must be directed between certain angles in a horizontal or vertical plane, or both.

Most practical transmitting antennas are divided into two basic classifications, HERTZ (half-wave) ANTENNAS and MARCONI (quarter-wave) ANTENNAS. Hertz antennas are generally installed some distance above the ground and are positioned to radiate either vertically or horizontally. Marconi antennas operate with one end grounded and are mounted perpendicular to the Earth or to a surface acting as a ground. Hertz antennas are generally used for frequencies above 2 megahertz. Marconi antennas are used for frequencies below 2 megahertz and may be used at higher frequencies in certain applications.

A complete antenna system consists of three parts: (1) The COUPLING DEVICE, (2) the FEEDER, and (3) the ANTENNA, as shown in figure 1-25. The coupling device (coupling coil) connects the transmitter to the feeder. The feeder is a transmission line that carries energy to the antenna. The antenna radiates this energy into space.

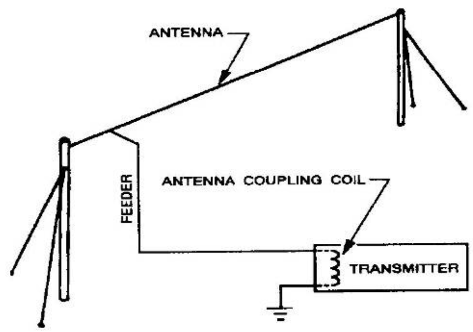

Figure 1-25.—Typical antenna system.

The factors that determine the type, size, and shape of the antenna are (1) the frequency of operation of the transmitter, (2) the amount of power to be radiated, and (3) the general direction of the receiving set. Typical antennas are shown in figure 1-26.

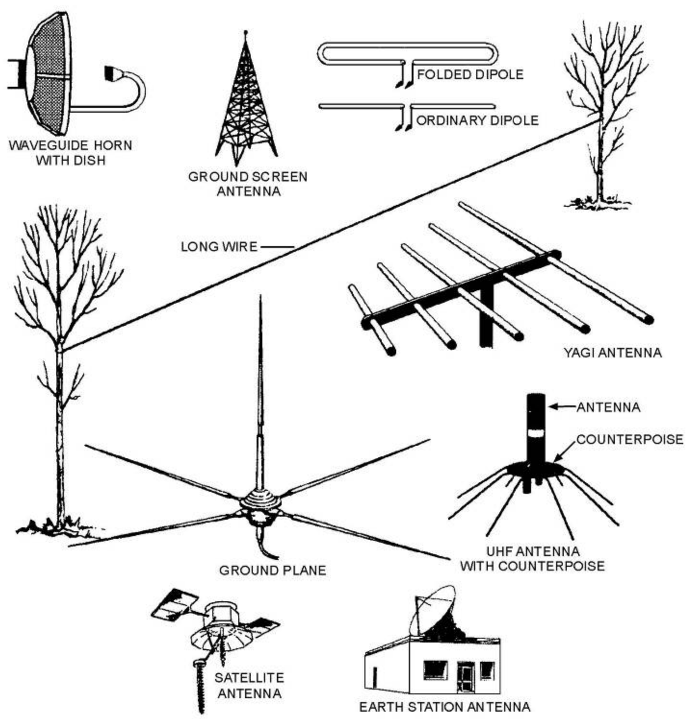

Figure 1-26.—Typical antennas.

Antenna Characteristics

You can define an antenna as a conductor or group of conductors used either for radiating electromagnetic energy into space or for collecting it from space. Electrical energy from the transmitter is converted into electromagnetic energy by the antenna and radiated into space. On the receiving end, electromagnetic energy is converted into electrical energy by the antenna and is fed into the receiver.

Fortunately, separate antennas seldom are required for both transmitting and receiving rf energy. Any antenna can transfer energy from space to its input receiver with the same efficiency that it transfers energy from the transmitter into space. Of course, this is assuming that the same frequency is used in both cases. This property of interchangeability of the same antenna for transmitting and receiving is known as antenna RECIPROCITY. Antenna reciprocity is possible because antenna characteristics are essentially the same for sending and receiving electromagnetic energy.

Reciprocity of Antennas

In general, the various properties of an antenna apply equally, regardless of whether you use the antenna for transmitting or receiving. The more efficient a certain antenna is for transmitting, the more efficient it will be for receiving on the same frequency. Likewise, the directive properties of a given antenna also will be the same whether it is used for transmitting or receiving.

Assume, for example, that a certain antenna used with a transmitter radiates a maximum amount of energy at right angles to the axis of the antenna, as shown in figure 1-27, view A. Note the minimum amount of radiation along the axis of the antenna. Now, if this same antenna were used as a receiving antenna, as shown in view B, it would receive best in the same directions in which it produced maximum radiation; that is, at right angles to the axis of the antenna.

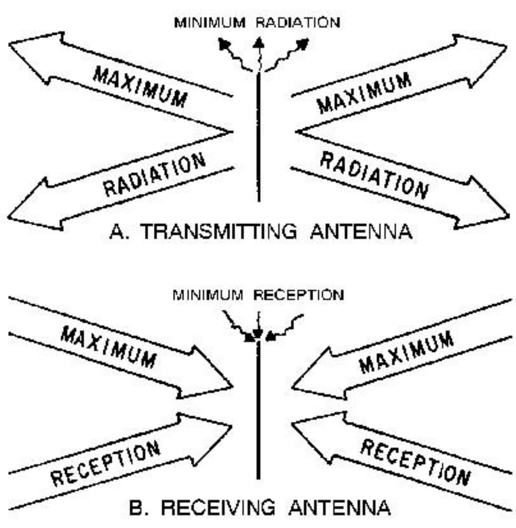

Figure 1-27.—Reciprocity of antennas.

Antenna Gain

Another characteristic of a given antenna that remains the same whether the antenna is used for transmitting or receiving is GAIN. Some antennas are highly directional that is, more energy is propagated in certain directions than in others. The ratio between the amount of energy propagated in these directions compared to the energy that would be propagated if the antenna were not directional is known as its gain. When a transmitting antenna with a certain gain is used as a receiving antenna, it will also have the same gain for receiving.

Polarization

The radiation field is composed of electric and magnetic lines of force. These lines of force are always at right angles to each other. Their intensities rise and fall together, reaching their maximums 90 degrees apart. The electric field determines the direction of polarization of the wave. In a vertically polarized wave, the electric lines of force lie in a vertical direction. In a horizontally polarized wave, the electric lines of force lie in a horizontal direction. Circular polarization has the electric lines of force rotating through 360 degrees with every cycle of rf energy.

<u>Advantages of Vertical Polarization</u>

Simple vertical antennas can be used to provide OMNIDIRECTIONAL (all directions) communication. This is an advantage when communications must take place from a moving vehicle.

In some overland communications, such as in vehicular installations, antenna heights are limited to 3 meters (10 feet) or less. In such instances vertical polarization results in a stronger receiver signal than does horizontal polarization at frequencies up to about 50 megahertz. From approximately 50 to 100 megahertz, vertical polarization results in a slightly stronger signal than does horizontal polarization with antennas at the same height. Above 100 megahertz, the difference in signal strength is negligible.

For transmission over bodies of water, vertical polarization is much better than horizontal polarization for antennas at the lower heights. As the frequency increases, the minimum antenna height decreases. At 30 megahertz, vertical polarization is better for antenna heights below about 91 meters (300 feet); at 85 megahertz, antenna heights below 15 meters (50 feet); and still lower heights at the high frequencies. Therefore, at ordinary antenna mast heights of 12 meters (40 feet), vertical polarization is advantageous for frequencies less than about 100 megahertz.

Radiation is somewhat less affected by reflections from aircraft flying over the transmission path when vertical polarization is used instead of horizontal polarization. With horizontal polarization, such reflections cause variations in received signal strength. This factor is important in locations where aircraft traffic is heavy.

When vertical polarization is used, less interference is produced or picked up because of strong vhf and uhf broadcast transmissions (television and fm). This is because vhf and uhf transmissions use horizontal polarization. This factor is important when an antenna must be located in an urban area having several television and fm broadcast stations.

Advantages of Horizontal Polarization

A simple horizontal antenna is bi-directional. This characteristic is useful when you desire to minimize interference from certain directions. Horizontal antennas are less likely to pick up man-made interference, which ordinarily is vertically polarized.
When antennas are located near dense forests or among buildings, horizontally polarized waves suffer lower losses than vertically polarized waves, especially above 100 megahertz. Small changes in antenna locations do not cause large variations in the field intensity of horizontally polarized waves. When vertical polarization is used, a change of only a few meters in the antenna location may have a considerable effect on the received signal strength. This is the result of interference patterns that produce standing waves in space when spurious reflections from trees or buildings occur.

When simple antennas are used, the transmission line, which is usually vertical, is less affected by a horizontally mounted antenna. When the antenna is mounted at right angles to the transmission line and horizontal polarization is used, the line is kept out of the direct field of the antenna. As a result, the radiation pattern and electrical characteristics of the antenna are practically unaffected by the presence of the vertical transmission line.

Basic Antennas

Before you look at the various types of antennas, consider the relationship between the wavelength at which the antenna is being operated and the actual length of the antenna. An antenna does not necessarily radiate or receive more energy when it is made longer. Specific dimensions must be used for efficient antenna operation.

Nearly all antennas have been developed from two basic types, the Hertz and the Marconi. The basic Hertz antenna is 1/2 wavelength long at the operating frequency and is insulated from ground. It is often called a DIPOLE or a DOUBLET. The basic Marconi antenna is 1/4 wavelength long and is either grounded at one end or connected to a network of wires called a COUNTERPOISE. The ground or counterpoise provides the equivalent of an additional 1/4 wavelength, which is required for the antenna to resonate.

Half-Wave Antennas

A half-wave antenna (referred to as a dipole, Hertz, or doublet) consists of two lengths of wire rod, or tubing, each 1/4 wavelength long at a certain frequency. It is the basic unit from which many complex antennas are constructed. The half-wave antenna operates independently of ground; therefore, it may be installed far above the surface of the Earth or other absorbing bodies.

Radiation Patterns

In the following discussion, the term DIPOLE is used to mean the basic half-wave antenna. The term DOUBLET is used to indicate an antenna that is very short compared with the wavelength of the operating frequency. Physically, it has the same shape as the dipole.

RADIATION PATTERN OF A DOUBLET.—The doublet is the simplest form of a practical antenna. Figure 1-28 shows the development of vertical and horizontal patterns for a doublet. This in NOT a picture of the radiation, but three-dimensional views of the pattern itself. In three views the pattern resembles a doughnut. From the dimensions in these views, two types of polar-coordinate patterns can be drawn, horizontal and vertical. The HORIZONTAL PATTERN view A is derived from the solid pattern view C by slicing it horizontally. This produces view B, which is converted to the polar coordinates seen in view

A. The horizontal pattern illustrates that the radiation is constant in any direction along the horizontal plane.

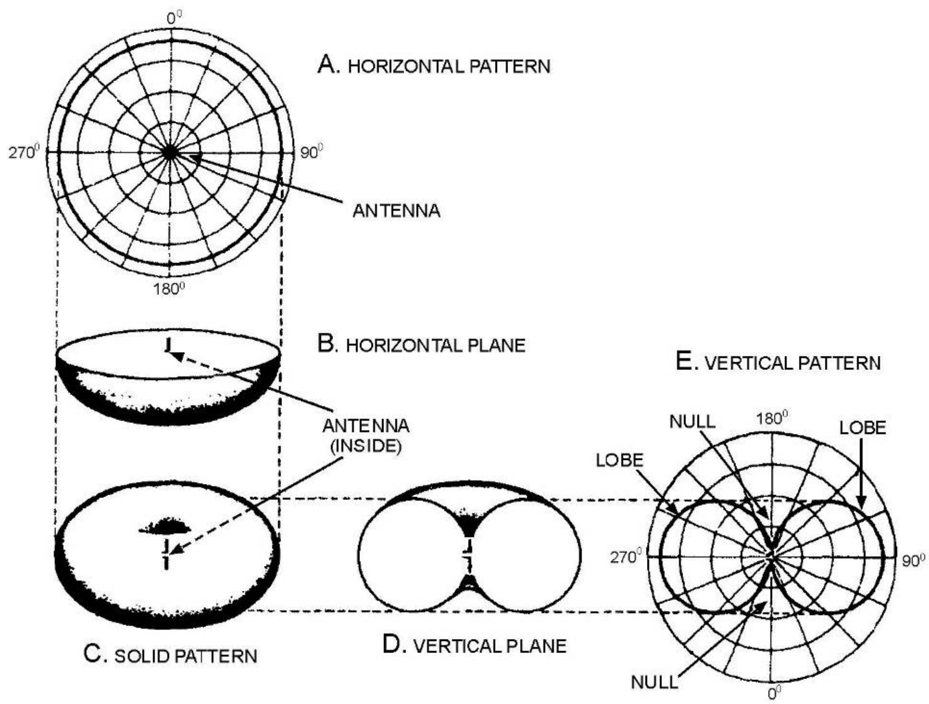

Figure 1-28.—Development of vertical and horizontal patterns.

A VERTICAL PATTERN view E is obtained from the drawing of the vertical plane view D of the radiation pattern view C. The radiation pattern view C is sliced in half along a vertical plane through the antenna. This produces the vertical plane pattern in view D. Note how the vertical plane in view D of the radiation pattern differs from the horizontal plane in view B. The vertical pattern view E exhibits two lobes and two nulls. The difference between the two patterns is caused by two facts: (1) no radiation is emitted from the ends of the doublet; and (2) maximum radiation comes from the doublet in a direction perpendicular to the antenna axis. This type of radiation pattern is both NONDIRECTIONAL (in a horizontal plane) and DIRECTIONAL (in a vertical plane).

From a practical viewpoint, the doublet antenna can be mounted either vertically or horizontally. The doublet shown in figure 1-28 is mounted vertically, and the radiated energy spreads out about the antenna in every direction in the horizontal plane. Since ordinarily the horizontal plane is the useful plane, this arrangement is termed NONDIRECTIONAL. The directional characteristics of the antenna in other planes is ignored. If the doublet were mounted horizontally, it would have the effect of turning the pattern on edge, reversing the patterns given in figure 4-14. The antenna would then be directional in the horizontal plane. The terms "directional" and "nondirectional" are used for convenience in describing specific radiation patterns. A complete description always involves a figure in three dimensions, as in the radiation pattern of figure 1-28.

☑Learning Check

32. What terms are often used to describe basic half-wave antennas?

33. If a basic half-wave antenna is mounted vertically, what type of radiation pattern will be produced?

34. In which plane will the half-wave antenna be operating if it is mounted horizontally?

RADIATION PATTERN OF A DIPOLE.—The radiation pattern of a dipole (fig. 1-29) is similar to that of the doublet (fig. 1-28). Increasing the length of the doublet to 1/2 wavelength has the effect of flattening out the radiation pattern. The radiation pattern in the horizontal plane of a dipole is a larger circle than that of the doublet. The vertical-radiation pattern lobes are no longer circular. They are flattened out and the radiation intensity is greater.

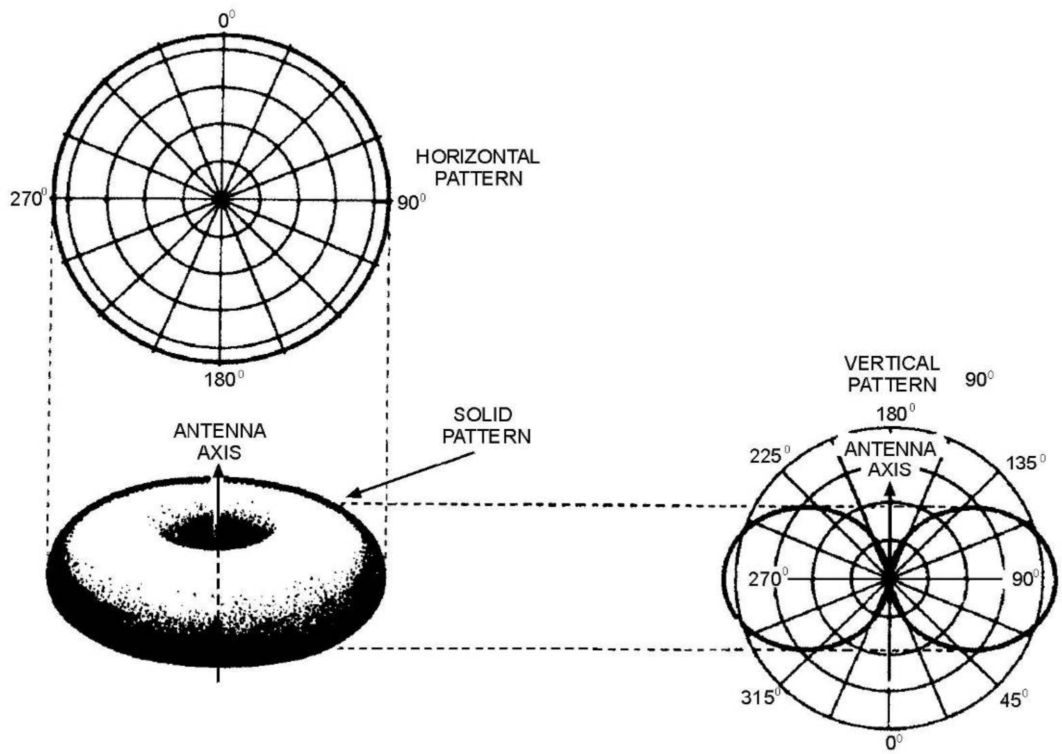

Figure 1-29.—Radiation pattern of a dipole.

Quarter-Wave Antennas

As you have studied in the previous sections, a 1/2 wavelength antenna is the shortest antenna that can be used in free space. If we cut a half-wave antenna in half and then ground one end, we will have a grounded quarter-wave antenna. This antenna will resonate at the same frequency as the ungrounded half-wave antenna. Such an antenna is referred to as a QUARTER-WAVE or Marconi antenna. Quarter-wave antennas are widely used in the military. Most mobile transmitting and receiving antennas (fig. 1-30) are quarter-wave antennas.

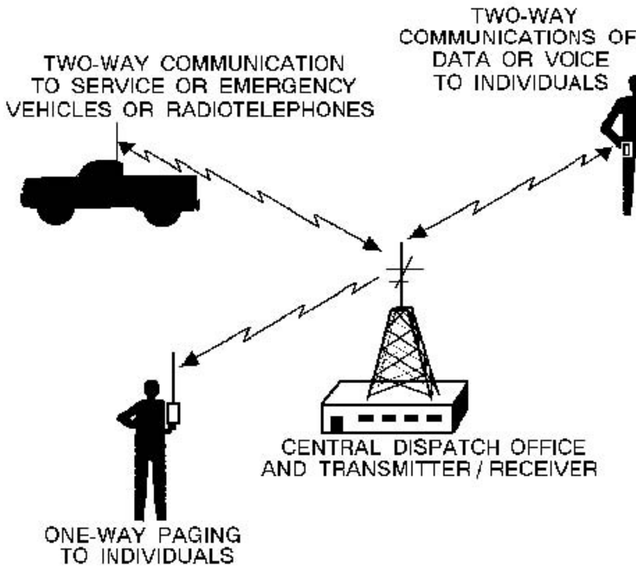

Figure 1-30.—Mobile antennas.

As stated above, a grounded quarter-wave antenna will resonate at the same frequency as an ungrounded half-wave antenna. This is because ground has high conductivity and acts as an electrical mirror image. This characteristic provides the missing half of the antenna, as shown in the bottom part of figure 1-31. In other words, the grounded quarter-wave antenna acts as if another quarter-wave were actually down in the earth.

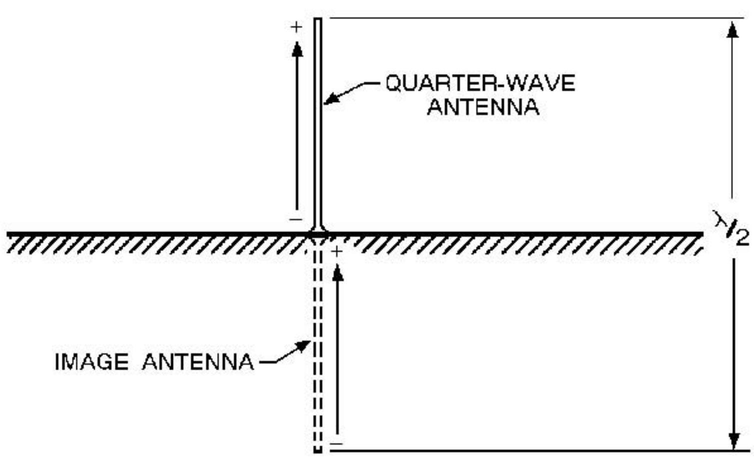

Figure 1-31.—Grounded quarter-wave antenna image.

Characteristics of Quarter-Wave Antennas

The grounded end of the quarter-wave antenna has a low input impedance and has low voltage and high current at the input end, as shown in figure 1-31. The ungrounded end has a high impedance, which causes high voltage and low current. The directional characteristics of a grounded quarter-wave antenna are the same as those of a half-wave antenna in free space.

As explained earlier, ground losses affect radiation patterns and cause high signal losses for some frequencies. Such losses may be greatly reduced if a perfectly conducting ground is provided in the vicinity of the antenna. This is the purpose of a GROUND SCREEN (figure 1-32, view A) and COUNTERPOISE view B.

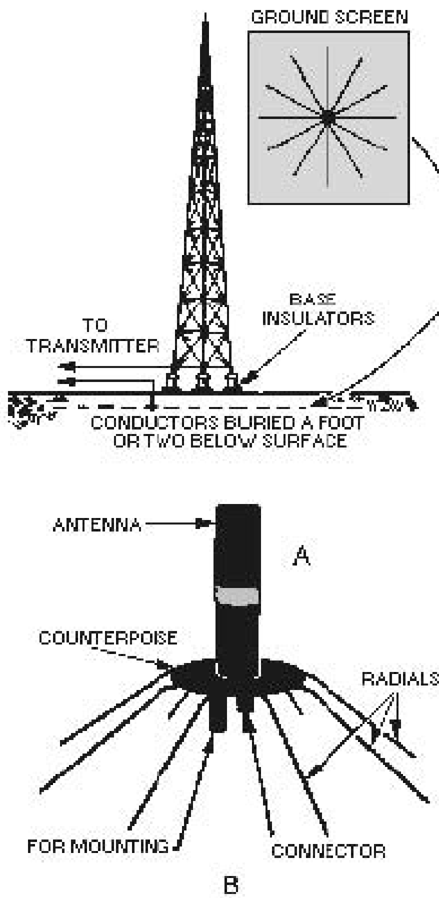

Figure 1-32.—Groundscreen and counterpoise.

The ground screen in view A is composed of a series of conductors buried 1 or 2 feet (0.3 to 0.6 meter) below the surface of the earth and arranged in a radial pattern. These conductors reduce losses in the ground in the immediate vicinity of the antenna. Such a radial system of conductors is usually 1/2 wavelength in diameter.

A counterpoise view B is used when easy access to the base of the antenna is necessary. It is also used when the earth is not a good conducting surface, such as ground that is sandy or solid rock. The counterpoise serves the same purpose as the ground screen but it is usually elevated above the earth. No specific dimensions are necessary in the construction of a counterpoise nor is the number of wires particularly critical. A practical counterpoise may be assembled from a large screen of chicken wire or some similar material. This screen may be placed on the ground, but better results are obtained if it is placed a few feet above the ground.

☑Learning Check

35. What is the radiation pattern of a quarter-wave antenna?

36. Describe the physical arrangement of a ground screen.

Folded Dipole

The use of parasitic elements and various stacking arrangements causes a reduction in the radiation resistance of a center-fed, half-wave antenna. Under these conditions obtaining a proper impedance match between the radiator and the transmission line is often difficult. A convenient method of overcoming these difficulties is to use a FOLDED DIPOLE in place of the center-fed radiator. (See views A and B of figure 1-33).

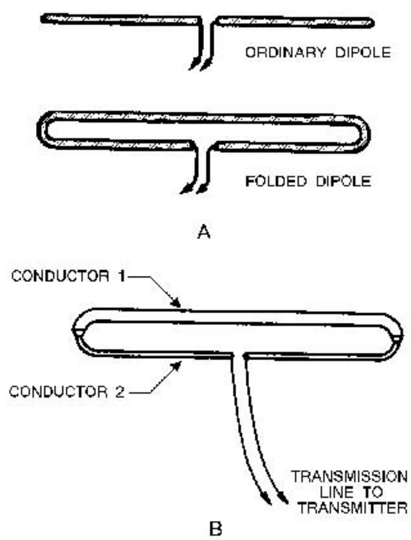

Figure 1-33.—Folded-dipole antennas.

A FOLDED DIPOLE is an ordinary half-wave antenna that has one or more additional conductors connected across its ends. Additional conductors are mounted parallel to the dipole elements at a distance equal to a very small fraction of a wavelength. Spacing of several inches is common.

The directional characteristics of a folded dipole are the same as those of a simple dipole. However, the reactance of a folded dipole varies much more slowly as the frequency is varied from resonance. Because of this the folded dipole can be used over a much wider frequency range than is possible with a simple dipole.

☑Learning Check

37. Which has a wider frequency range, a simple dipole or a folded dipole?

Array Antennas

An array antenna is a special arrangement of basic antenna components involving new factors and concepts. Before you begin studying about arrays, you need to study some new terminology.

Arrays can be described with respect to their radiation patterns and the types of elements of which they are made. However, you will find it useful to identify them by the physical placement of the elements and the direction of radiation with respect to these elements. Generally speaking, the term BROADSIDE ARRAY designates an array in which the direction of maximum radiation is perpendicular to the plane containing these elements. In actual practice, this term is confined to those arrays in which the elements themselves are also broadside, or parallel, with respect to each other.

A COLLINEAR ARRAY is one in which all the elements lie in a straight line with no radiation at the ends of the array. The direction of maximum radiation is perpendicular to the axis of the elements.

The FRONT-TO-BACK RATIO is the ratio of the energy radiated in the principal direction compared to the energy radiated in the opposite direction for a given antenna.

Directivity

The DIRECTIVITY of an antenna or an array can be determined by looking at its radiation pattern. In an array propagating a given amount of energy, more radiation takes place in certain directions than in others. The elements in the array can be altered in such a way that they change the pattern and distribute it more uniformly in all directions. The elements can be considered as a group of antennas fed from a common source and facing different directions. On the other hand, the elements could be arranged so that the radiation would be focused in a single direction. With no increase in power from the transmitter, the amount of radiation in a given direction would be greater. Since the input power has no increase, this increased directivity is achieved at the expense of gain in other directions.

Directivity and Interference

In many applications, sharp directivity is desirable although no need exists for added gain. Examine the physical disposition of the units shown in figure 1-34. Transmitters 1 and 2 are sending information to receivers 1 and 2, respectively, along the paths shown by the solid arrows. The distance between transmitter 1 and receiver 1 or between transmitter 2 and receiver 2 is short and does not require high-power transmission. The antennas of the transmitters propagate well in all directions. However, receiver 1 picks up some of the signals from transmitter 2, and receiver 2 picks up some of the signals from transmitter 1, as shown by the broken arrows. This effect is emphasized if the receiving antennas intercept energy equally well in all directions.

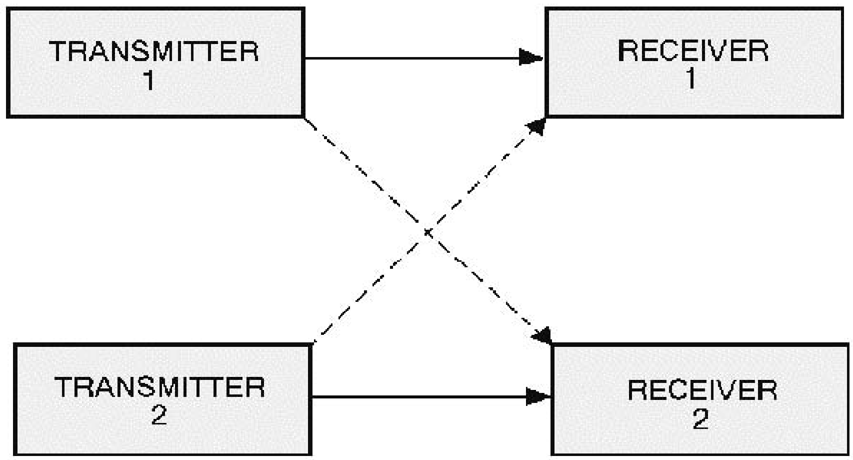

Figure 1-34.—Directivity and interference.

The use of highly directional arrays as radiators from the transmitters tends to solve the problem. The signals are beamed along the paths of the solid arrows and provide very low radiation along the paths of the broken arrows. Further improvement along these lines is obtained by the use of narrowly directed arrays as receiving antennas. The effect of this arrangement is to select the desired signal while discriminating against all other signals. This same approach can be used to overcome other types of radiated interference. In such cases, preventing radiation in certain directions is more important than producing greater gain in other directions.

Look at the differences between the field patterns of the single-element antenna and the array, as illustrated in figure 1-35. View A shows the relative field-strength pattern for a horizontally polarized single antenna. View B shows the horizontal-radiation pattern for an array. The antenna in view A radiates fairly efficiently in the desired direction toward receiving point X. It radiates equally as efficiently toward Y, although no radiation is desired in this direction. The antenna in view B radiates strongly to point X, but very little in the direction of point Y, which results in more satisfactory operation.

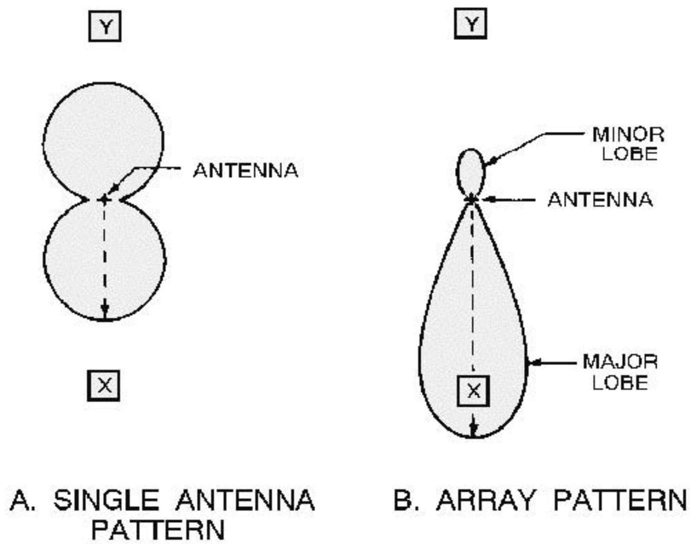

Figure 1-35.—Single antenna versus array.

Major and Minor Lobes

The pattern shown in figure 1-35, view B, has radiation concentrated in two lobes. The radiation intensity in one lobe is considerably stronger than in the other. The lobe toward point X is called a MAJOR LOBE; the other is a MINOR LOBE. Since the complex radiation patterns associated with arrays frequently contain several lobes of varying intensity, you should learn to use appropriate terminology. In general, major lobes are those in which the greatest amount of radiation occurs. Minor lobes are those in which the radiation intensity is least.

☑Learning Check

38. What is the primary difference between the major and minor lobes of a radiation pattern?

Directional Arrays

You have already learned about radiation patterns and directivity of radiation. These topics are important to you because using an antenna with an improper radiation pattern or with the wrong directivity will decrease the overall performance of the system. In the following paragraphs, we discuss in more detail the various types of directional antenna arrays mentioned briefly in the "definition of terms" paragraph above.

Collinear Array

The pattern radiated by the collinear array is similar to that produced by a single dipole. The addition of the second radiator, however, tends to intensify the pattern. Compare the radiation pattern of the dipole (view A of figure 1-36) and the two-element antenna in view B. You will see that each pattern consists of two major lobes in opposite directions along the same axis, QQ1. There is little or no radiation along the PP1 axis. QQ1 represents the line of maximum propagation. You can see that radiation is stronger with an added element. The pattern in view B is sharper, or more directive, than that in view A. This means that the gain along the line of maximum energy propagation is increased and the beam width is decreased. As more elements are added, the effect is heightened, as shown in view C. Unimportant minor lobes are generated as more elements are added.

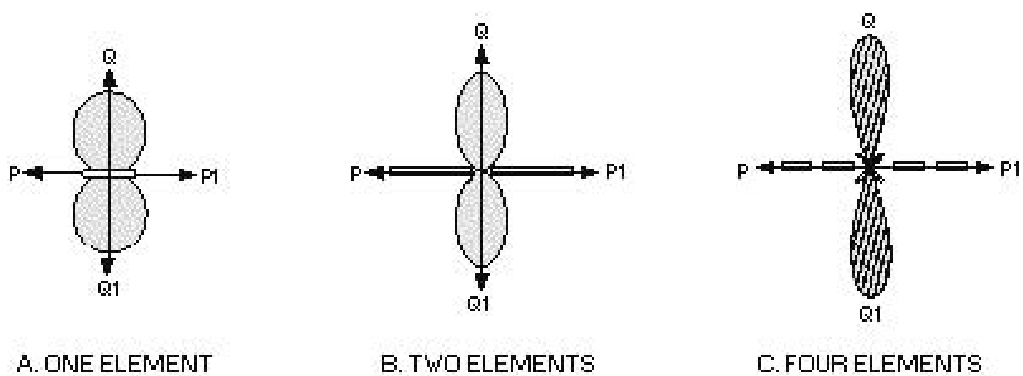

Figure 1-36.—Single half-wave antenna versus two half-wave antennas in phase.

More than four elements are seldom used because accumulated losses cause the elements farther from the point of feeding to have less current than the nearer ones. This introduces an unbalanced condition in the system and impairs its efficiency. Space limitations often are another reason for restricting the number of elements. Since this type of array is in a single line, rather than in a vertically stacked arrangement, the use of too many elements results in an antenna several wavelengths long.

RADIATION PATTERN.—The characteristic radiation pattern of a given array is obtained at the frequency or band of frequencies at which the system is resonant. The gain and directivity characteristics are lost when the antenna is not used at or near this frequency and the array tunes too sharply. A collinear antenna is more effective than an end-fire array when used off its tuned frequency. This feature is considered when transmission or reception is to be over a wide frequency band. When more than two elements are used, this advantage largely disappears.

Multielement Parasitic Array

A MULTIELEMENT PARASITIC array is one that contains two or more parasitic elements with the driven element. If the array contains two parasitic elements (a reflector and a director) in addition to the driven element, it is usually known as a THREE-ELEMENT ARRAY. If three parasitic elements are used, the array is known as a FOUR-ELEMENT ARRAY, and so on. Generally speaking, if more parasitic elements are added to a three-element array, each added element is a director. The field behind a reflector is so small that additional reflectors would have little effect on the overall radiation pattern. In radar, from one to five directors are used.

CONSTRUCTION.—The parasitic elements of a multi-element parasitic array usually are positioned as shown in figure 1-37, views A and B. Proper spacings and lengths are determined experimentally. A folded dipole (view B) is often used as the driven element to obtain greater values of radiation resistance.

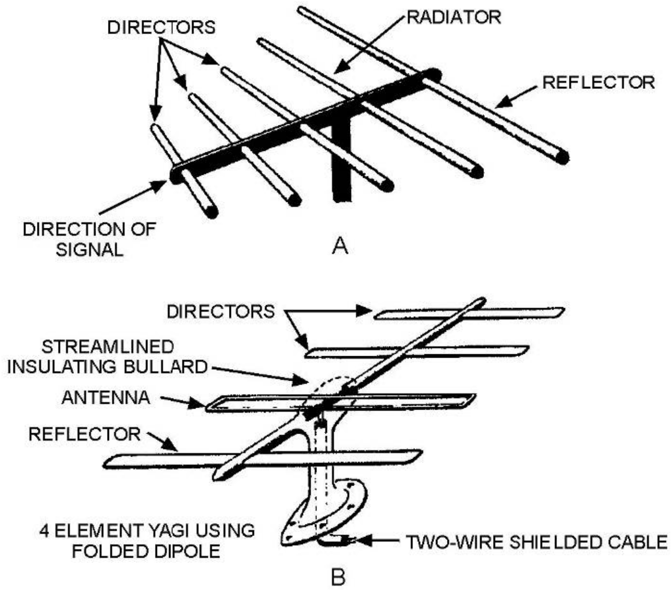

Figure 1-37.—Yagi antenna.

YAGI ANTENNAS.—An example of a multielement parasitic array is the YAGI ANTENNA (figure 1-37, views A and B). The spacings between the elements are not uniform. The radiation from the different elements arrives in phase in the forward direction, but out of phase by various amounts in the other directions.

The director and the reflector in the Yagi antenna are usually welded to a conducting rod or tube at their centers. This support does not interfere with the operation of the antenna. Since the driven element is center-fed, it is not welded to the supporting rod. The center impedance can be increased by using a folded dipole as the driven element.

The Yagi antenna shown in figure 1-37, view A, has three directors. In general, the greater number of parasitic elements used, the greater the gain. However, a greater number of such elements causes the array to have a narrower frequency response as well as a narrower beamwidth. Therefore, proper adjustment of the antenna is critical. The gain does not increase directly with the number of elements used. For example, a three-element Yagi array has a relative power gain of 5 dB. Adding another director results in a 2 dB increase. Additional directors have less and less effect.

☑**Learning Check**

39. What is the advantage of adding parasitic elements to a Yagi array?

40. The Yagi antenna is an example of what type of array?

Ground-Plane Antenna

A vertical quarter-wave antenna several wavelengths above ground produces a high angle of radiation that is very undesirable at vhf and uhf frequencies. The most common means of producing a low angle of radiation from such an antenna is to work the radiator against a simulated ground called a GROUND PLANE. A simulated ground may be made from a large metal sheet or several wires or rods radiating from the base of the radiator. An antenna so constructed is known as a GROUND-PLANE ANTENNA. Two ground-plane antennas are shown in figure 1-38, views A and B.

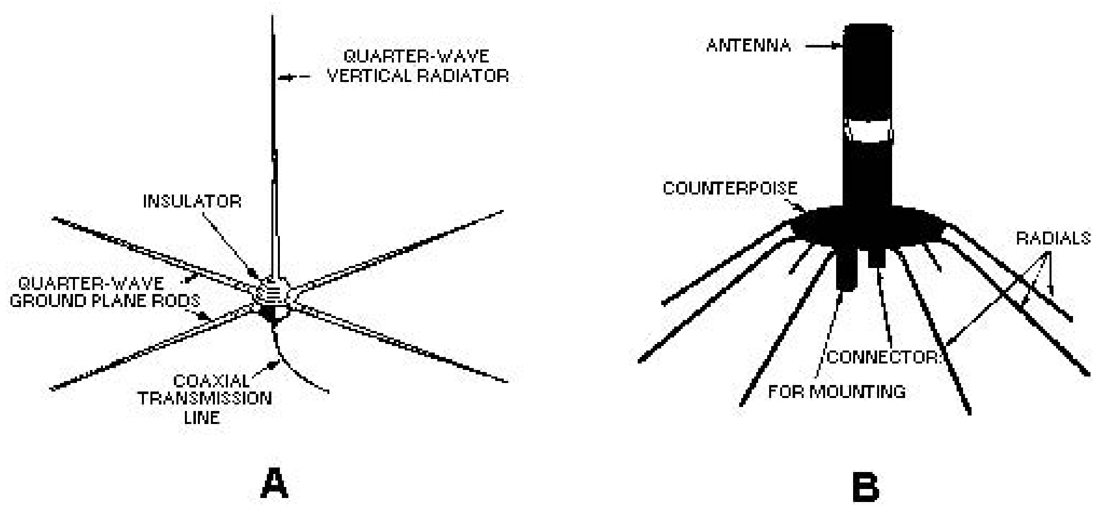

Figure 1-38.—Ground-plane antennas.

Corner Reflector

When a unidirectional radiation pattern is desired, it can be obtained by the use of a corner reflector with a half-wave dipole. A CORNER-REFLECTOR ANTENNA is a half-wave radiator with a reflector. The reflector consists of two flat metal surfaces meeting at an angle immediately behind the radiator. In other words, the radiator is set in the plane of a line bisecting the corner angle formed by the reflector sheets. The construction of a corner reflector is shown in figure 1-39. Corner-reflector antennas are mounted with the radiator and the reflector in the horizontal position when horizontal polarization is desired. In such cases the radiation pattern is very narrow in the vertical plane, with maximum signal being radiated in line with the bisector of the corner angle. The directivity in the horizontal plane is approximately the same as for any half-wave radiator having a single-rod type reflector behind it. If the antenna is mounted with the radiator and the corner reflector in the vertical position, as shown in view A, maximum radiation is produced in a very narrow horizontal beam. Radiation in a vertical plane will be the same as for a similar radiator with a single-rod type reflector behind it.

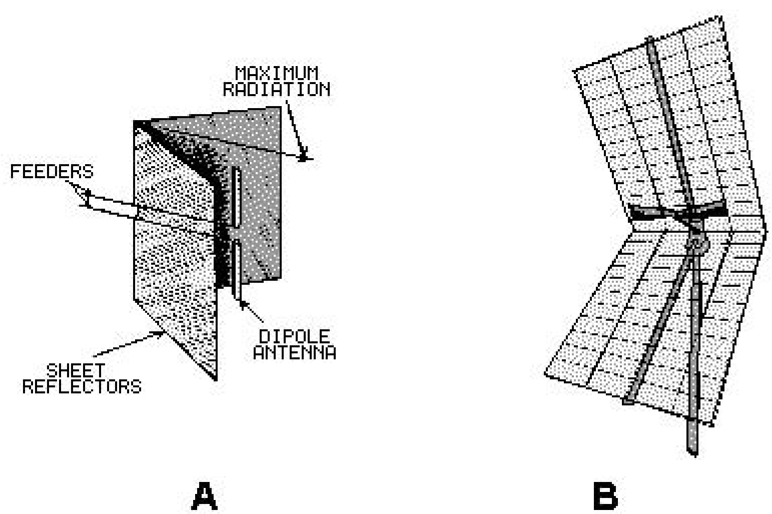

Figure 1-39.—Corner-reflector an

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SUMMARY AND EVALUATION OF TRAINING

Summary

You have completed this workbook, and now you should be able to

- State what radio waves are;
- List the components of a radio wave and define the terms cycle, frequency, harmonics, period, wavelength, and velocity as applied to radio wave propagation;
- Compute the wavelength of radio waves;
- State how radio waves are polarized, vertically and horizontally;
- State what reflection, refraction, and diffraction are as applied to radio waves;
- State what influence the Earth's atmosphere has on radio waves and list the different layers of the Earth's atmosphere;
- Identify a ground wave, a sky wave, and state the effects of the ionosphere on the sky wave;
- Describe propagation paths;
- Describe fading, multipath fading;
- Describe propagation paths;
- State how transmission losses affect radio wave propagation;
- State how electromagnetic interference, man-made/natural interference, and ionospheric disturbances affect radio wave propagation. State how transmission losses affect radio wave propagation;
- State what temperature inversion is, how frequency predictions are made, and how weather affects frequency;
- State what tropospheric scatter is and how it affects radio wave propagation;
- State what a transmission line is and how transmission lines are used;
- Describe the five types of transmission lines;
- State the basic principles of antenna radiation and list the parts of an antenna;
- Describe how electromagnetic energy is radiated from an antenna;
- Explain polarization, gain, and radiation resistance characteristics of an antenna;
- Describe the theory of operation of half- wave and quarter-wave antennas;
- List the various array antennas;

- Describe the directional array antennas presented and explain the basic operation of each; and
- Identify various special antennas presented, such as ground-plane, and corner-reflector; describe the operation of each.

Evaluation of Training

We value your input and we need your help in making this a better instructional product. Please complete the training evaluation form found on the next page. Be sure to leave the form in the workbook as it will be collected when you attend the Communications Specialist Course.

Evaluation of Training
Volume 2: Radio Wave Propagation and Antennas

Date: ____________________

1. Were the objectives accomplished?	**Y**	**N**
Comments:		
2. Were the topics and exercises applicable and relevant to your job?	**Y**	**N**
Identify by name:		
3. Was there material presented that you felt was NOT applicable to your job (i.e., not useful information)?	**Y**	**N**
Identify topics:		
4. Did the sequencing of the instruction seem appropriate (i.e., was there a logical flow)?	**Y**	**N**
Comments:		
5. Did the learning checks effectively evaluate your accomplishment of the objectives?	**Y**	**N**
Comments:		
6. Did you feel the content was adequately covered without overkill?	**Y**	**N**
Comments:		

Please write any additional comments and suggestions: