NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical and Electronic Engineering

RADIO WAVE PROPAGATION

Graduation project
EE- 400

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TABLE OF CONTENTS

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I am deeply indebted to my parents for their love and there endless support. They have always encouraged me to pursue my interest and ambitions throughout life. I would never achieve my current position without my family.

To my sisters who give me all love and respects. Hana, Nada, Maha, Sana.

I wish them all to live happily always.

To all my friends especially özlem YOUNIS, maen AMOSE, allam HIJAWI.

To all of them,all my love .

LIST OF ABBREVIATIONS

LF	Low Frequency
MF	Medium Frequency
HF	High Frequency
VHF	Very High Frequency
UHF	Ultra High Frequency
SHF	Super High Frequency
EHF	Extremely High Frequency
emi	Electromagnetic Interference
luf	Lowest Usable Frequency
sid	Sudden Ionospheric Disturbance
muf	Maximum Usable Frequensy
BER	bit error rate
SNR	signal to noise ratio
LOS	WaveLANLoss on Line of Sight Links
non-LOS	Path Loss on Non-Line of Sight Paths
RFProp	RF Propagation
ISI	intersymbol interference
SS	spread spectrum
DSSS	Direct Sequence
FHSS	Frequency Hopping
OFDM	Orthogonal Frequency Division Multiplex

LIST OF SYMBOLS

A	Area
s	Power flux density
d	Distant
h	Height
λ	Wave length in meter
f	Frequency of radio wave
P_t	Transmitter power output (dBm or dBW, same units as P_r)
L_p	Free space path loss between isotropic antennas (dB)
G_t	Transmit antenna gain (dBi)
G_r	Receive antenna gain (dBi)
L_t	Transmission line loss between transmitter and transmit antenna (dB)
L_r	Transmission line loss between receive antenna and receiver input (dB)
η	Index of refraction
μ	Magnetic permeability
ε	Dielectric constant
ω_B	Frequency of precession of a charged particle in a magnetic field
NZ	Density of electrons per unit volume

TABLE OF FIGURE

ABSTRACT

The radio communication system is the one of the most important part in communication world, consists of a transmitter, antenna, propagation medium and receiver.

However, in this project we will confine to those conditions, which arise in and between the transmitting antenna and the receiving antenna, with reference to performance of receivers when appropriate.

This project attempts to provide some insight into the nature of radio propagation in that part of the spectrum (upper Electromagnetic Fields, Radio Wave&Polarization, The Effect Of the earth's atmosphere on radio waves , Frequency Selection Considerations ,VHF to Microwave, Indoor Radio Propagation)

This project is dedicated to providing a simplified overview for some of the important ionosphere mechanics used in propagation research as well as discussing limitations due to the complex dynamics of the ionosphere. Because the physics of ionospheric radio wave propagation is an extremely vast and complex topic, to describe the physics of ionospheric radio wave refraction in a short and concise manner without overwhelming the reader requires that certain assumptions be made. Although these assumptions may appear to oversimplify the problem at first,

By used experimenters for high-speed digital transmission. It begins with the basics of free space path loss calculations, and then considers the effects of refraction, diffraction and reflections on the path loss of Line of Sight (LOS) links.

The nature of non-LOS radio links is then examined, and propagation effects other than path loss, which are important in digital transmission, are also described.

INTRODUCTION

We had thought to do our work on the radio wave propagation, and we will discus the important subject since the radio wave one of the most important and famous part in the communication system.

The term radio wave is defending by dictionary as wave of radio but in institute of electrical and electronic engineering (IEEE) is an energy wave generated by transmitter.

The main emphasis of this project is on predicting the path loss of a link, so that one can approach the installation of the antennas and other RF equipment with some degree of confidence that the link will work. The focus is on acquiring a feel for radio propagation, and pointing the way towards recognizing the alternatives that may exist and the instances in which experimentation may be fruitful.

We'll also look at some propagation aspects, which are of particular relevance to digital signaling.

We will start from the electromagnetic fields because use it is the basic of the any wave subject

Finishing chapter one. In the 2^{nd} & 3^{rd} chapter our discussion will explain the earth's atmosphere and its effect on radio wave and the polarization and will know how radio wave transmitted in its two principal.

A basic understanding of the ionosphere properties is paramount to understanding HF radio propagation over distance. This page is dedicated to providing a simplified overview for some of the important ionosphere mechanics used in propagation research as well as discussing limitations due to the complex dynamics of the ionosphere. Because the physics of ionospheric radio wave propagation is an extremely vast and complex topic, to describe the physics of ionospheric radio wave refraction in a short and concise manner without overwhelming the reader requires that certain assumptions be made. Although these assumptions may appear to oversimplify the problem at first, the predictions made by the final solution of the Equation of Motion do adequately describe the observations made by radio wave propagation experiments; therefore, the following physics has formed the basis of understanding of this problem in research groups around the world. In my summary, I have included supporting data for these conclusions that were obtained by recent HF radio testing using the PTC-II HF controller to derive HF radio skip distance over a range of HF frequencies. Finally, in the physics below, Gaussian units will be utilized and all vectors will be denoted in bold. Also, in order to properly view the mathematical equations, you will need to keep the fonts setting in your preference menu set to the document-specified fonts position.

Since we come to the last subject covering the previous chapters we will conceder the frequency selection consideration in the 4th chapter, and talk abut VHF/UHF/Microwave Radio Propagation in the 5th chapter.

Indoor use of wireless systems poses one of the biggest design challenges, as indoor radio (RF) propagation is essentially a Black Art. This technical note will try to shed some light on this mysterious subject and will seek to quantify or set boundaries for use of wireless systems inside typical buildings at 900 MHz and 2.4 GHz. That will be the of 6th chapter

CHAPTER 1

ELECTROMAGNETIC FIELDS

1.1 Electromagnetic Fields

The way energy is propagated into free space is a source of great dispute among people concerned with it. Although many theories have been proposed, the following theory adequately explains the phenomena and has been widely accepted. There are two basic fields associated with every antenna; an INDUCTION FIELD and a RADIATION FIELD. The field associated with the energy stored in the antenna is the induction field. This field is said to provide no part in the transmission of electromagnetic energy through free space. However, without the presence of the induction field, there would be no energy radiated.

1.1.1 Induction Field

Figure 1-1, a low-frequency generator connected to an antenna, will help you understand how the induction field is produced. Let's follow the generator through one cycle of operation.

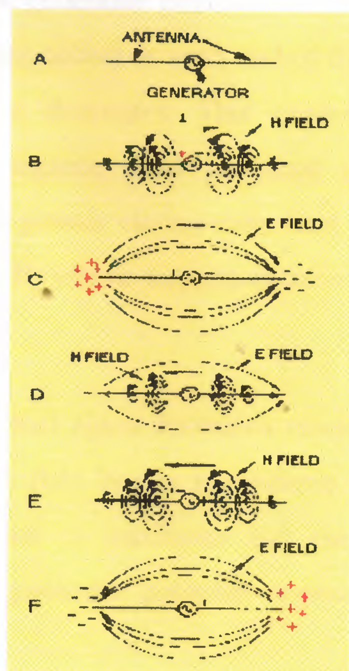

Figure 1.1 Induction Field About An Antenna

Initially, you and that no fields exist about the antenna, as shown in view A. Now assume that the generator produces a slight potential and has the instantaneous polarity shown in view B. Because of this slight potential, the antenna capacitance acts as a short, allowing a large flow of current (I) through the antenna in the direction shown. This current flow, in turn, produces a large magnetic field about the antenna.

Since the flow of current at each end of the antenna is minimum, the corresponding magnetic fields at each end of the antenna are also minimum. As time passes, charges, which oppose antenna current and produce an electrostatic field (E field), collect at each end of the antenna. Eventually, the antenna capacitance becomes fully charged and stops current flow through the antenna. Under this condition, the electrostatic field is maximum, and the magnetic field (H field) is fully collapsed, as shown in view C.

As the generator potential decreases back to zero, the potential of the antenna begins to discharge. During the discharging process, the electrostatic field collapses and the direction of current flow reverses, as shown in view D. When the current again begins to flow, an associated magnetic field is generated. Eventually, the electrostatic field completely collapses, the generator potential reverses, and current are maximum, as shown in view E. As charges collect at each end of the antenna, an electrostatic field is produced and current flow decreases. This causes the magnetic field to begin collapsing. The collapsing magnetic field produces more current flow, a greater accumulation of charge, and a greater electrostatic field. The antenna gradually reaches the condition shown in view F, where current is zero and the collected charges are maximum.

As the generator potential again decreases toward zero, the antenna begins to discharge and the electrostatic field begins to collapse. When the generator potential reaches zero, discharge current is maximum and the associated magnetic field is maximum. A brief time later, generator potential reverses, and the condition shown in view B recurs.

NOTE: The electric field (E field) and the electrostatic field (E field) are the same. They will be used interchangeably throughout this text.

The graph shown in figure 1-2 shows the relationship between the magnetic (H) field and the electric (E) field plotted against time. Note that the two fields are 90 degrees out of phase with each other. If you compare the graph in figure 1-2 with figure 1-1, you will notice that the two fields around the antenna are displaced 90 degrees from each other in space. (The H field exists in a plane perpendicular to the antenna. The E field exists in a plane parallel with the antenna, as shown in figure 1-1.)

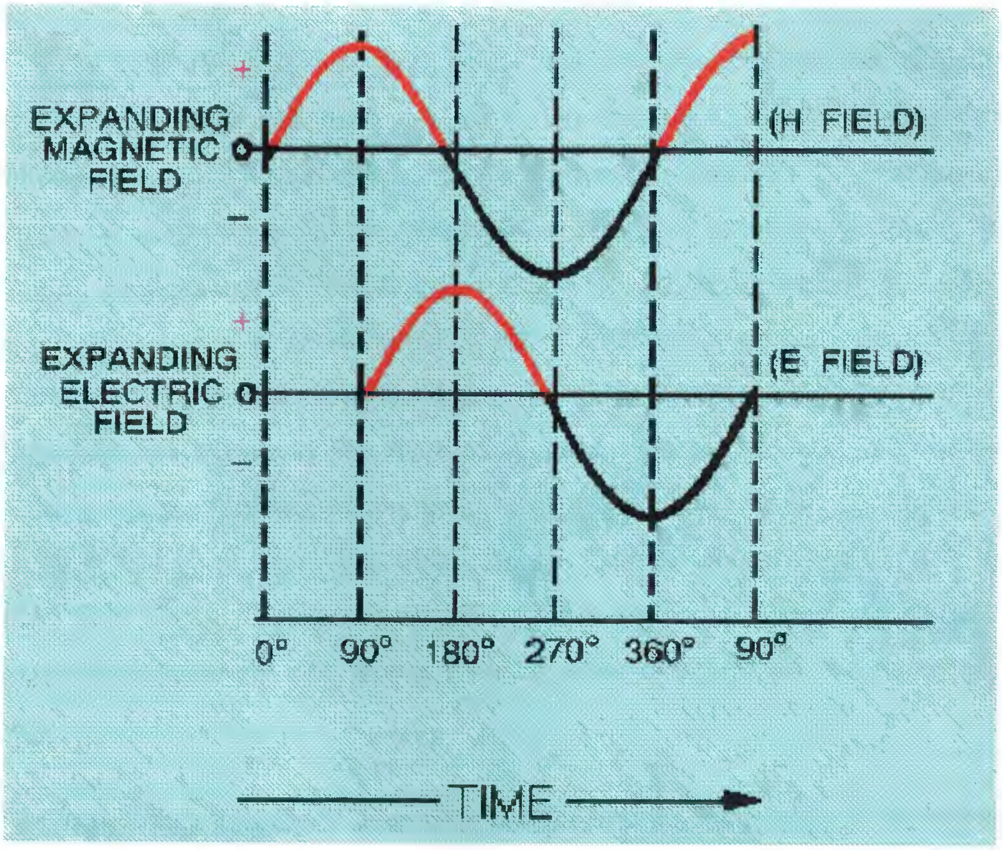

FIGURE 1.2 Phase Relationship of Induction field Components .

All the energy supplied to the induction field is returned to the antenna by the collapsing E and H fields. No energy from the induction field is radiated from the antenna. Therefore, the induction field is considered a local field and plays no part in the transmission of electromagnetic energy. The induction field represents only the stored energy in the antenna and is responsible only for the resonant effects that the antenna reflects to the generator.

1.1.2 Radiation Fields

The E and H fields that are set up in the transfer of energy through space are known collectively as the radiation field. This radiation field is responsible for electromagnetic radiation from the antenna. The radiation field decreases as the distance from the antenna is increased. Because the decrease is linear, the radiation field reaches great distances from the antenna.

Let's look at a half-wave antenna to illustrate how this radiation actually takes place. Simply stated, a half-wave antenna is one that has an electrical length equal to half the wavelength of the signal being transmitted. Assume, for example, that a transmitter is operating at 30 megahertz. If a half-wave antenna were used with the transmitter, the antenna's electrical length would have to be at least 16 feet long. (The formula used to compute the electrical length of an antenna will be explained in chapter 4.) When power is delivered to the half-wave antenna, both an induction field and a radiation field are set up by the fluctuating energy. At the antenna, the intensities of these fields are proportional to the amount of power delivered to the antenna from a source such as a transmitter. At a short distance from the antenna and beyond, only the radiation field exists. This radiation field is made up of an electric component and a magnetic component at right angles to each other in space and varying together in intensity.

With a high-frequency generator (a transmitter) connected to the antenna, the induction field is produced as described in the previous section. However, the generator potential reverses before the electrostatic field has had time to collapse completely. The reversed generator potential neutralizes the remaining antenna charges, leaving a resultant E field in space.

Figure 1-3 is a simple picture of an E field detaching itself from an antenna. (The H field will not be considered, although it is present.) In view A the voltage is maximum and the electric field has maximum intensity. The lines of force begin at the end of the antenna that is positively charged and extend to the end of the antenna that is negatively charged. Note that the outer E lines are stretched away from the inner lines. This is because of the repelling force that takes place between lines of force in the same direction. As the voltage drops (view B), the separated charges come together, and the ends of the lines move toward the center of the antenna. But, since lines of force in the same direction repel each other, the centers of the lines are still being held out.

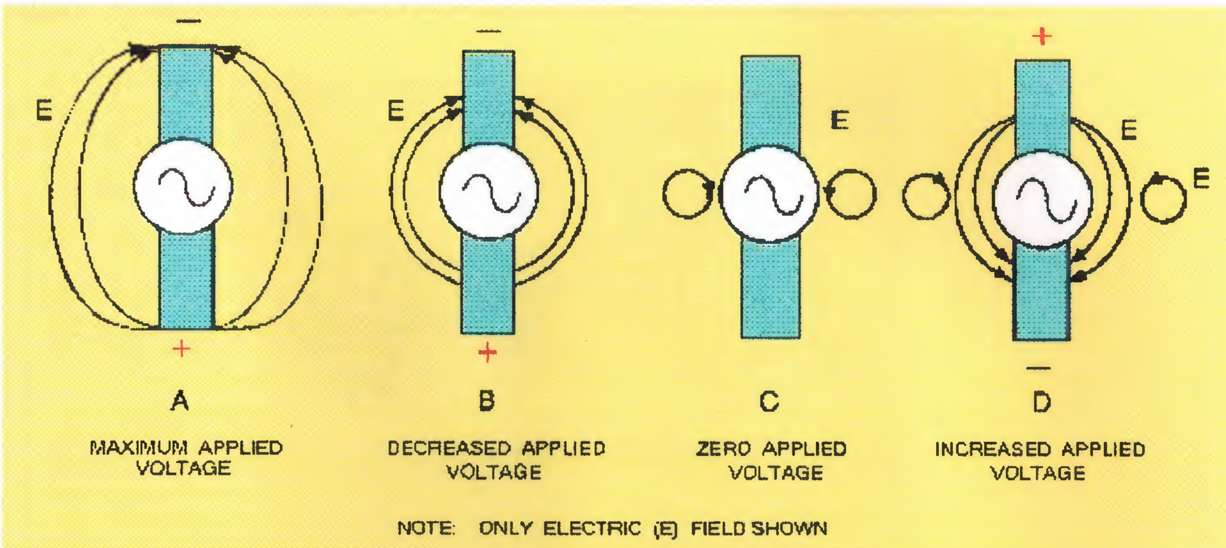

FIGURE 1.3 Radiation from an Antenna .

As the voltage approaches zero (view B), some of the lines collapse back into the antenna. At the same time, the ends of other lines begin to come together to form a complete loop. Notice the direction of these lines of force next to the antenna in view C. At this point the voltage on the antenna is zero. As the charge starts to build up in the opposite direction (view D), electric lines of force again begin at the positive end of the antenna and stretch to the negative end of the antenna. These lines of force, being in the same direction as the sides of the closed loops next to the antenna, repel the closed loops and force them out into space at the speed of light. As these loops travel through space, they generate a magnetic field in phase with them.

Since each successive E field is generated with a polarity that is opposite the preceding E field (that is, the lines of force are opposite), an oscillating electric field is produced along the path of travel. When an electric field oscillates, a magnetic field having an intensity that varies directly with that of the E field is produced. The variations in magnetic field intensity, in turn, produce another E field. Thus, the two varying fields sustain each other, resulting in electromagnetic wave propagation.

During this radiation process, the E and H fields are in phase in time but physically displaced 90 degrees in space. Thus, the varying magnetic field produces a varying electric field; and the varying electric field, in turn, sustains the varying magnetic field. Each field supports the other, and neither can be propagated by itself. Figure 1-4 shows a comparison between the induction field and the radiation field.

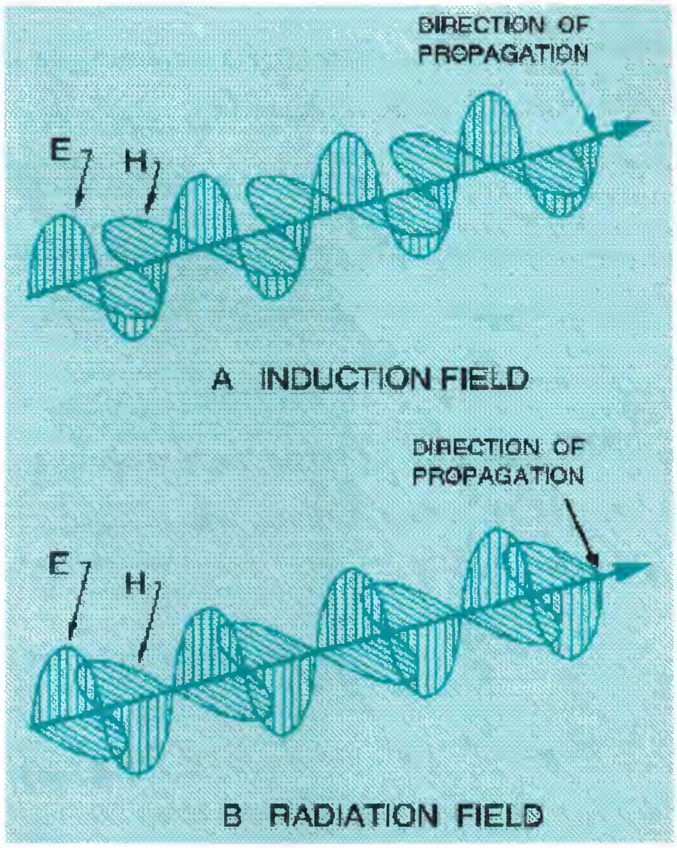

FIGURE 1.4 E and H Components of Induction and Radiation Fields.

CHPTER 2

RADIOWAVES& POLARIZATION

2.1 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. All the principles of wave motion that were discussed in chapter 1 also apply to radio waves.

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

2.1.1 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 2-1. 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
Ultra high	UHF	300 to 3000 MHz
Superhigh	SHF	3 to 30 GHz
Extremely high	EHF	30 to 300 GHz

Any frequency that is a whole number multiple of a smaller basic frequency is known as a HARMONIC of that basic frequency. The basic frequency itself is called the first harmonic or, more commonly, the FUNDAMENTAL FREQUENCY. A frequency that is twice as great as the fundamental frequency is called the second harmonic; a frequency three times as great is the third harmonic; and so on. For example:

First harmonic (Fundamental frequency)	3000 kHz
Second harmonic	6000 kHz
Third harmonic	9000 kHz

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 relationship between frequency, wavelength, and antennas will be discussed in chapter 4 of this module.

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.

2.1.2 Wavelenghth-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 theHIGHER 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:

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

Given:

$$\lambda = 240 \text{ meters}$$

Solution:

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

$$f = 1250kHz$$

To find the frequency in megahertz, use the formula:

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

Given:

$$\lambda = 240 \text{ meters}$$

Solution:

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

$$f = 1.25MHz$$

2.2 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 2-1, 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.

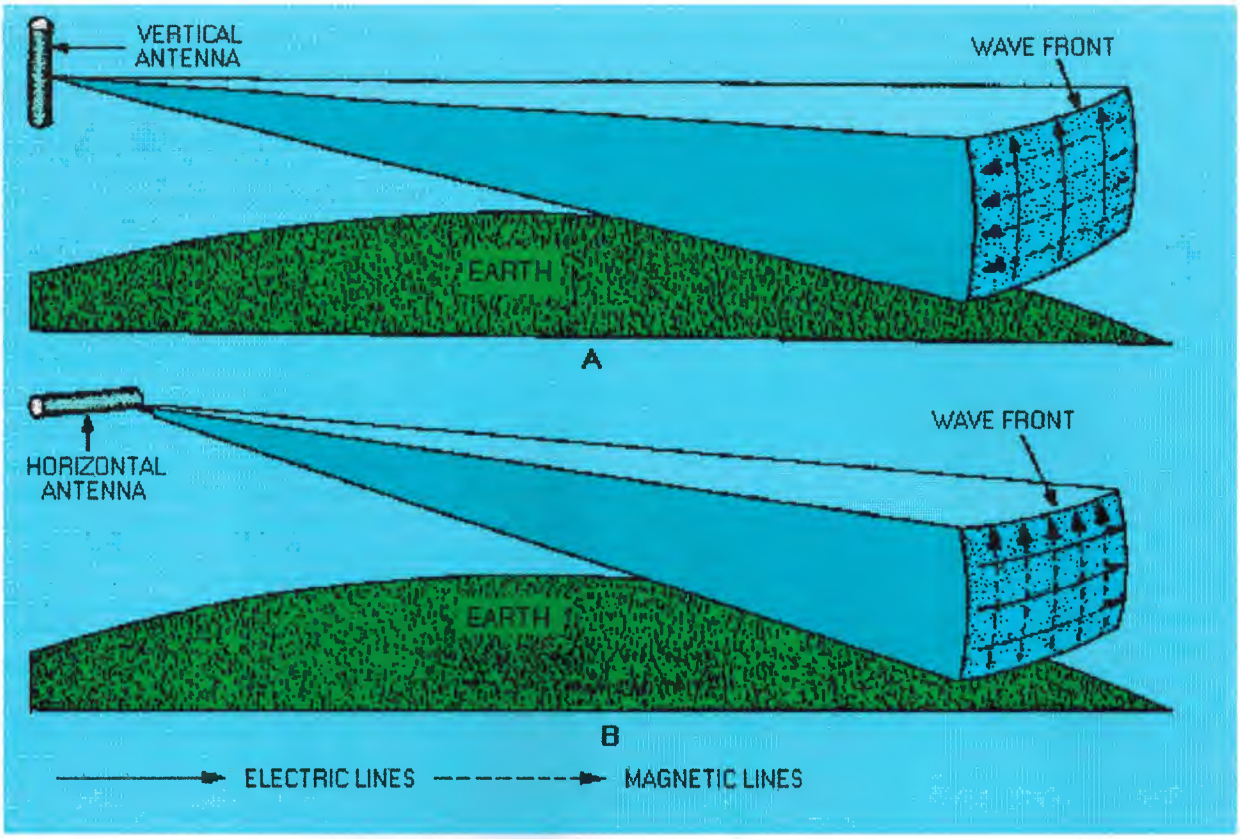

FIGURE 2.1 Vertical And Horizontal Polarization.

The position of the antenna in space is important because it affects the polarization of the electromagnetic wave. When the transmitting antenna is close to the ground, vertically polarized waves cause greater signal strength along the Earth's surface. On the other hand, antennas high above the ground should be horizontally polarized to get the greatest possible signal strength to the Earth's surface. Vertically and horizontally polarized antennas will be discussed in more detail in.

The radiated energy from an antenna is in the form of an expanding sphere. Any small section of this sphere is perpendicular to the direction the energy travels and is called a WAVEFRONT. All energy on a waterfront is in phase. Usually all points on the waterfront are at equal distances from the antenna. The farther the waterfront is from the antenna, the less spherical the wave appears. At a considerable distance the waterfront can be considered as a plane surface at a right angle to the direction of propagation.

If you know the directions of the E and H components, you can use the "right-hand rule" (see figure 2-2) to determine the direction of wave propagation . This rule states that if the thumb, forefinger, and middle finger of the right hand are extended so they are mutually perpendicular, the middle finger will point in the direction of wave propagation if the thumb points in the direction of the E field and the forefinger points in the direction of the H field. Since both the E and H fields reverse directions simultaneously, propagation of a particular waterfront is always in the same direction (away from the antenna).

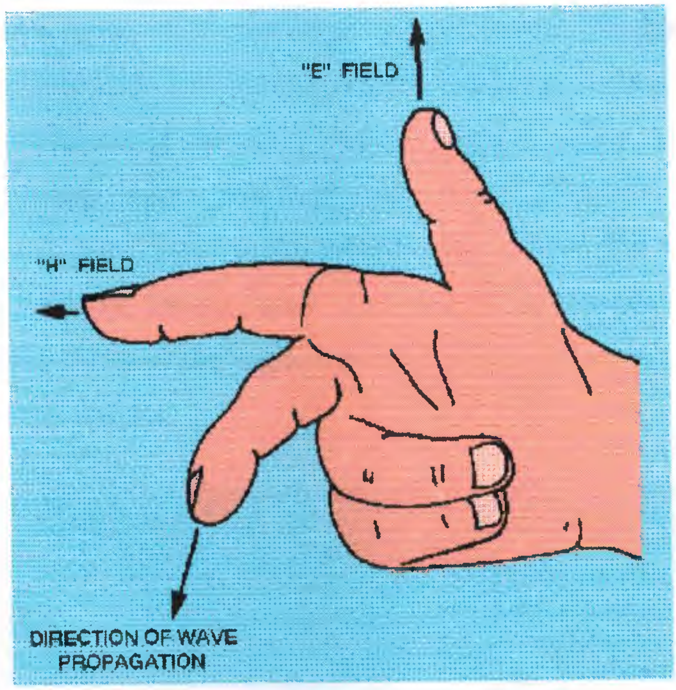

FIGURE 2.2 Right-Hand Rule for Propagation.

2.3 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 2-3 shows two radio waves being reflected from the Earth's surface. Notice that the positive and negative alternations of radio waves (A) and (B) are in phase with each other in their paths toward the Earth's surface. After reflection takes place, however, the waves are approximately 180 degrees out of phase from their initial relationship. The amount of phase shift that occurs is not constant. It depends on the polarization of the wave and the angle at which the wave strikes the reflecting 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.

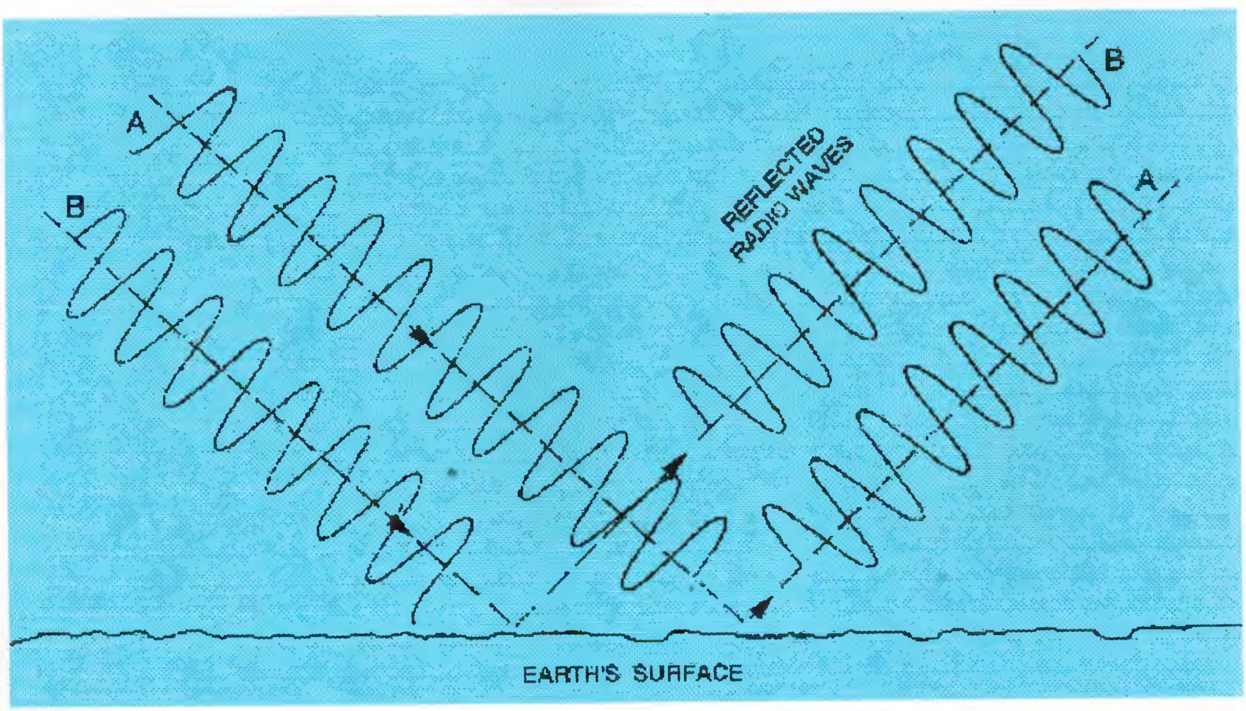

FIGURE 2.3 Phase Shift of Reflected Radio Waves.

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 2-4 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.

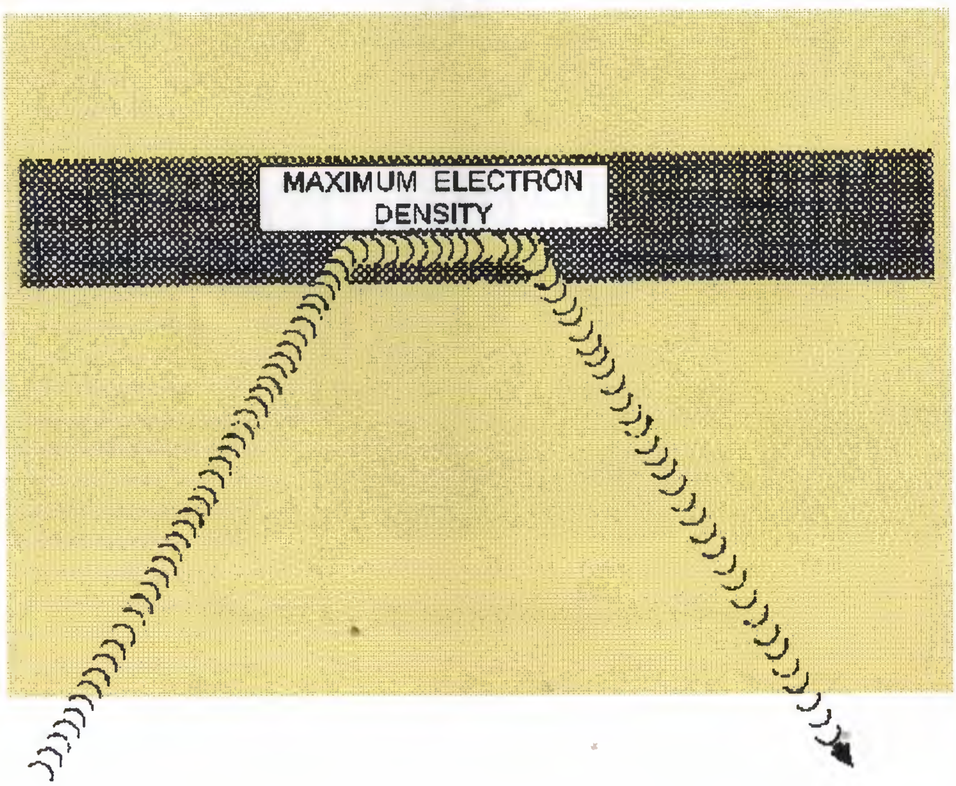

FIGURE 2.4 Radio Wave Refraction.

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 2-5. 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.

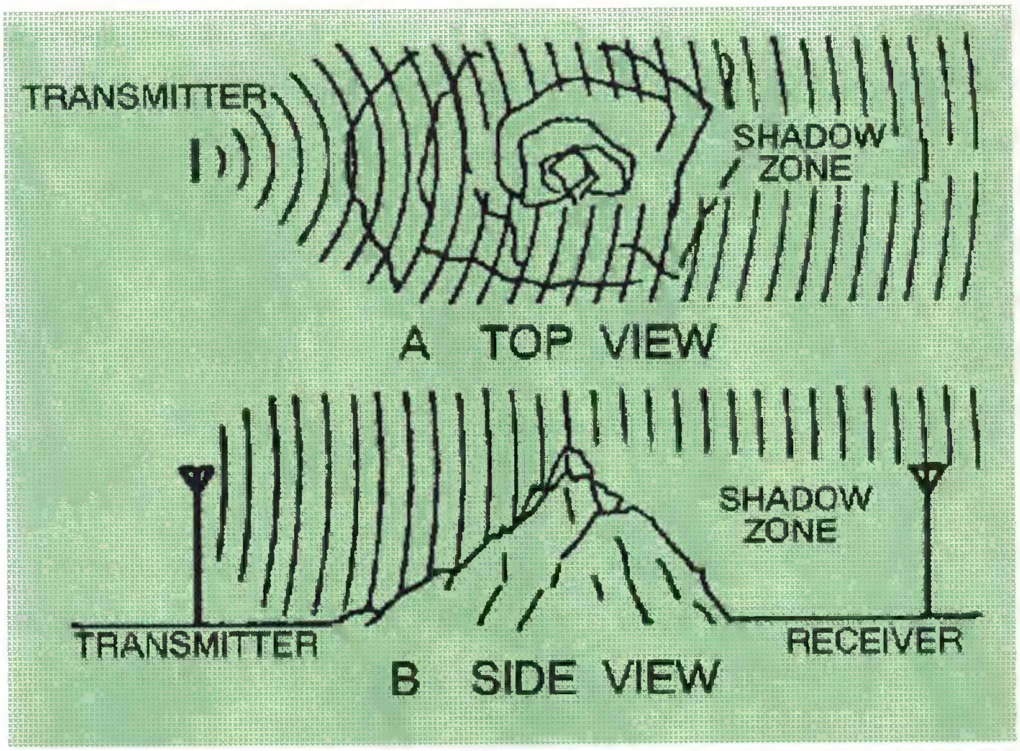

FIGURE 2.5 Diffraction Around An Object.

CHAPTER 3

THE EFFECT of THE EARTH'S ATMOSPHERE on RADIO WAVES & RADIO WAVE TRANSMISSION

3.1 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 figure 3-1.

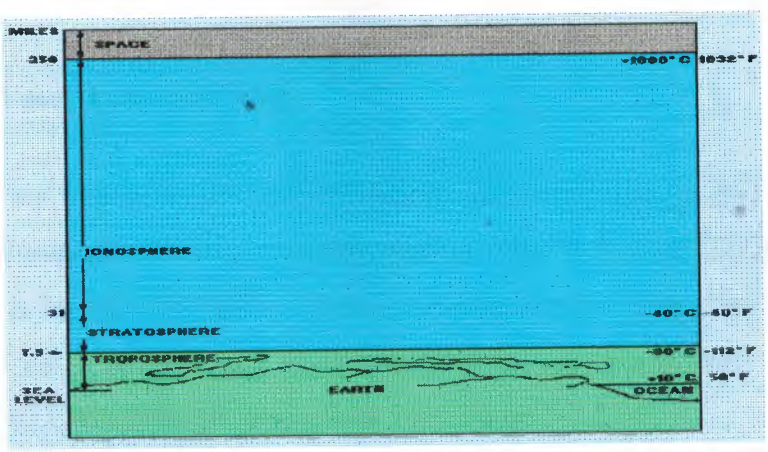

FIGURE 3.1 Layers of The Earth's Atmosphere.

3.1.1 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.

3.1.2 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.

3.1.3 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. This region will be discussed in detail a little later in this chapter.

3.2 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 3-2.)

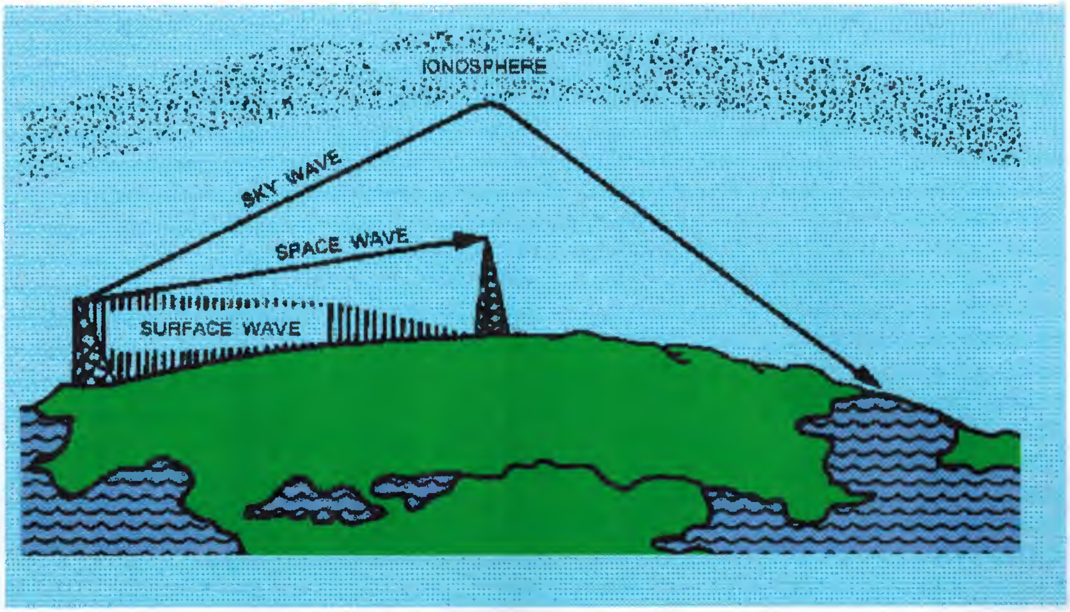

FIGURE 3.2 Ground Waves and Sky Waves.

Ground Waves . -The ground wave is actually composed of two separate component waves. These are known as the SURFACE WAVE and the SPACE WAVE (fig3-3). 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 <u>along</u> the surface of the Earth. A space wave travels <u>over</u> the surface.

Surface Wave. - The surface wave reaches the receiving site by traveling along the surface of the ground as shown in figure 3-3. 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.

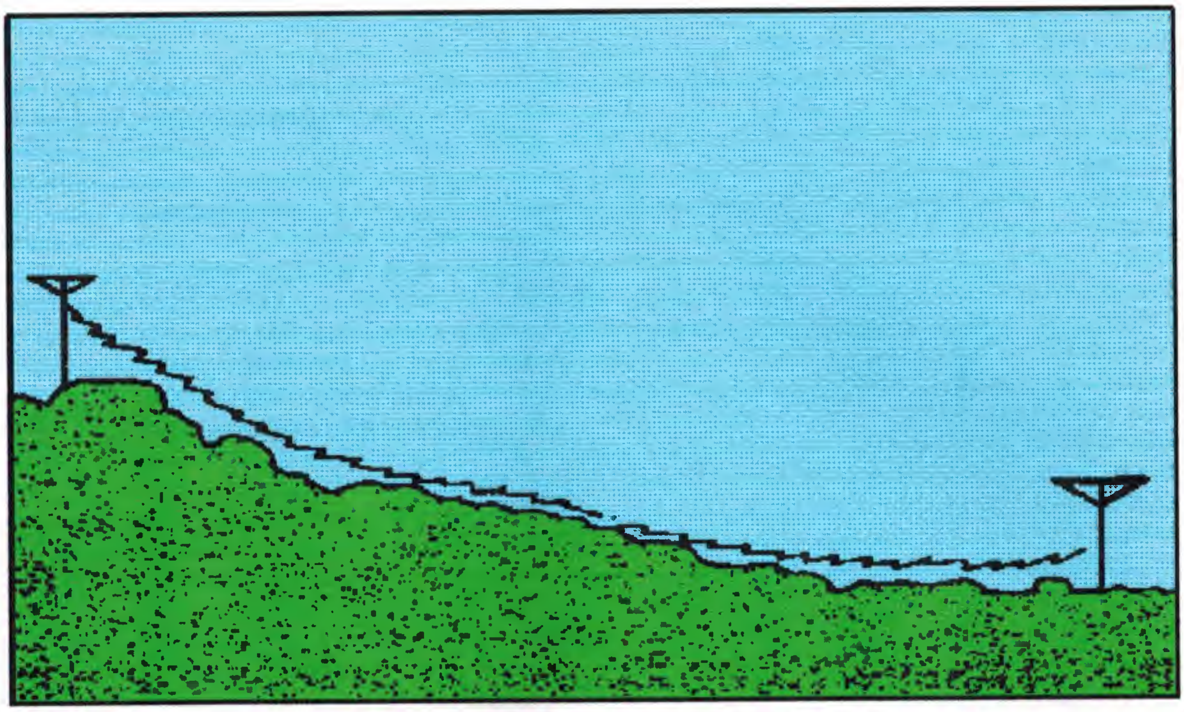

FIGURE 3.3 Surface Wave Propagation.

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 3-1 gives the relative conductivity of various surfaces of the Earth.

Table 1-1. - Radio Frequency Bands

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. The Navy's extremely high-powered vlf transmitters are actually capable of transmitting surface wave signals around the Earth and can provide coverage to naval units operating anywhere at sea.

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 3-3. 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.

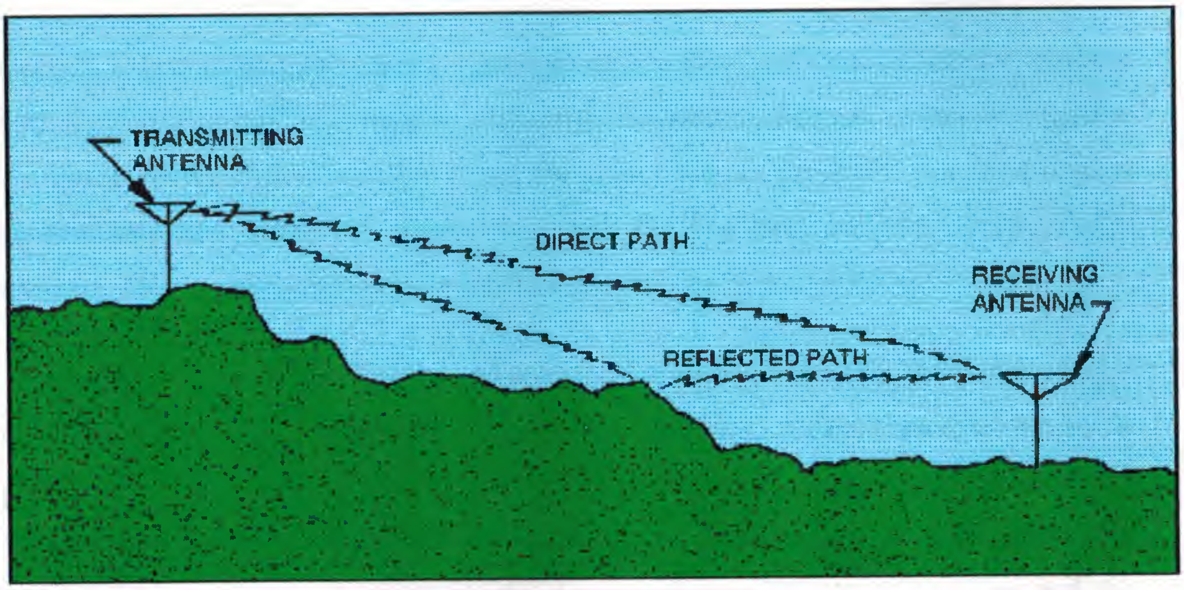

FIGURE 3.4 Space Wave Propagation.

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 result in a weak or fading signal.

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. The following in-depth study of the ionosphere and its effect on sky waves will help you to better understand the nature of sky wave propagation.

3.2.1 Structure of The Ionosphere

As we stated earlier, the ionosphere is the region of the atmosphere that extends from about 30 miles above the surface of the Earth to about 250 miles. It is appropriately named the ionosphere because it consists of several layers of electrically charged gas atoms called ions. The ions are formed by a process called ionization.

Ionization. - Ionization occurs when high energy ultraviolet light waves from the sun enter the ionospheric region of the atmosphere, strike a gas atom, and literally knock an electron free from its parent atom. A normal atom is electrically neutral since it contains both a positive proton in its nucleus and a negative orbiting electron. When the negative electron is knocked free from the atom, the atom becomes positively charged (called a positive ion) and remains in space along with the free electron, which is negatively charged. This process of upsetting electrical neutrality is known as IONIZATION.

The free negative electrons subsequently absorb part of the ultraviolet energy, which initially freed them from their atoms. As the ultraviolet light wave continues to produce positive ions and negative electrons, its intensity decreases because of the absorption of energy by the free electrons, and an ionized layer is formed. The rate at which ionization occurs depends on the density of atoms in the atmosphere and the intensity of the ultraviolet light wave, which varies with the activity of the sun.

Since the atmosphere is bombarded by ultraviolet light waves of different frequencies, several ionized layers are formed at different altitudes. Lower frequency ultraviolet waves penetrate the atmosphere the least; therefore, they produce ionized layers at the higher altitudes. Conversely, ultraviolet waves of higher frequencies penetrate deeper and produce layers at the lower altitudes.

An important factor in determining the density of ionized layers is the elevation angle of the sun, which changes frequently. For this reason, the height and thickness of the ionized layers vary, depending on the time of day and even the season of the year.

Recombination. - Recall that the process of ionization involves ultraviolet light waves knocking electrons free from their atoms. A reverse process called RECOMBINATION occurs when the free electrons and positive ions collide with each other. Since these collisions are inevitable, the positive ions return to their original neutral atom state.

The recombination process also depends on the time of day. Between the hours of early morning and late afternoon, the rate of ionization exceeds the rate of recombination. During this period, the ionized layers reach their greatest density and exert maximum influence on radio waves. During the late afternoon and early evening hours, however, the rate of recombination exceeds the rate of ionization, and the density of the ionized layers begins to decrease. Throughout the night, density continues to decrease, reaching a low point just before sunrise.

Four Distinct Layers. - The ionosphere is composed of three layers designated D, E, and F, from lowest level to highest level as shown in figure 3-4. The F layer is further divided into two layers designated F1 (the lower layer) and F2 (the higher layer). The presence or absence of these layers in the ionosphere and their height above the Earth varies with the position of the sun. At high noon, radiation in the ionosphere directly above a given point is greatest. At night it is minimum. When the radiation is removed, many of the particles that were ionized recombine. The time interval between these conditions finds the position and number of the ionized layers within the ionosphere changing. Since the position of the sun varies daily, monthly, and yearly, with respect to a specified point on Earth, the exact position and number of layers present are extremely difficult to determine. However, the following general statements can be made:

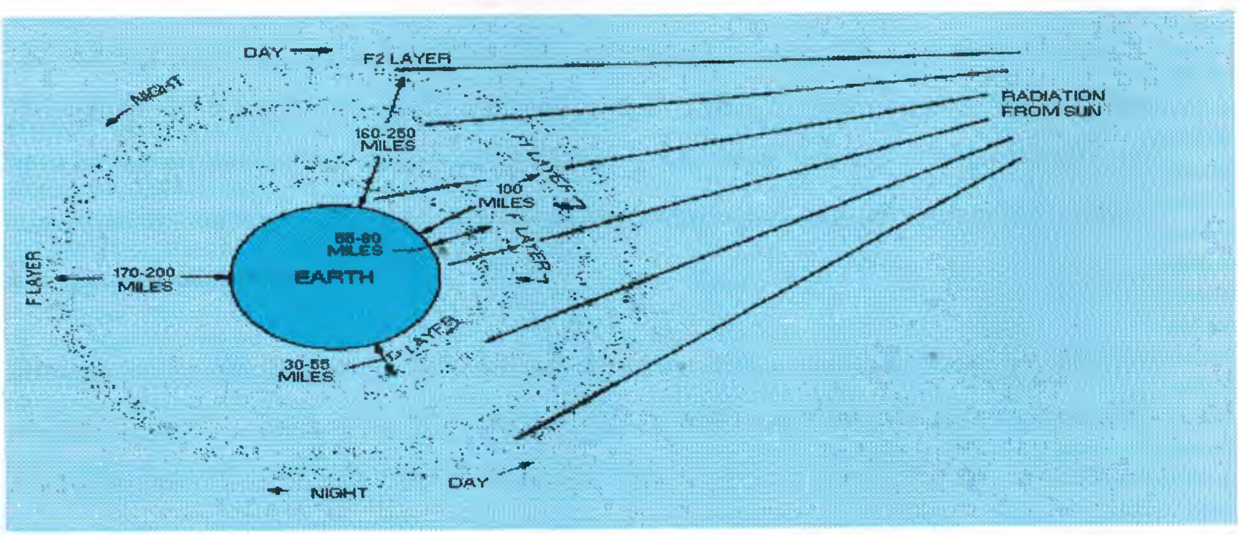

FIGURE 3-5. - Layers of The Ionosphere.

1. The D layer ranges from about 30 to 55 miles. Ionization in the D layer is low because it is the lowest region of the ionosphere. This layer has the ability to refract

signals of low 6frequencies. High frequencies pass right through it and are attenuated. After sunset, the D layer disappears because of the rapid recombination of ions.

2. The E layer limits are from about 55 to 90 miles. This layer is also known as the Kennelly-Heaviside layer, because these two men were the first to propose its existence. The rate of ionic recombination in this layer is rather rapid after sunset and the layer is almost gone by midnight. This layer has the ability to refract signals as high as 20 megahertz. For this reason, it is valuable for communications in ranges up to about 1500 miles.

3. The F layer exists from about 90 to 240 miles. During the daylight hours, the F layer separates into two layers, the F1 and F2 layers. The ionization level in these layers is quite high and varies widely during the day. At noon, this portion of the atmosphere is closest to the sun and the degree of ionization is maximum. Since the atmosphere is rarefied at these heights, recombination occurs slowly after sunset. Therefore, a fairly constant ionized layer is always present. The F layers are responsible for high-frequency, long distance transmission.

3.2.2 Refraction in The Ionsphere

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.

Density of Layer Figure 3-7 illustrates the relationship between radio waves and ionization density. Each ionized layer has a central region of relatively dense ionization, which tapers off in intensity both above and below the maximum region. As a radio wave enters a region of INCREASING ionization, the increase in velocity of the upper part of the wave causes it to be bent back TOWARD the Earth. While the wave is in the highly dense center portion of the layer, however, refraction occurs more slowly because the density of ionization is almost uniform. As the wave enters into the upper signals of low 6frequencies. High frequencies pass right through it and are attenuated. After sunset, the D layer disappears because of the rapid recombination of ions.

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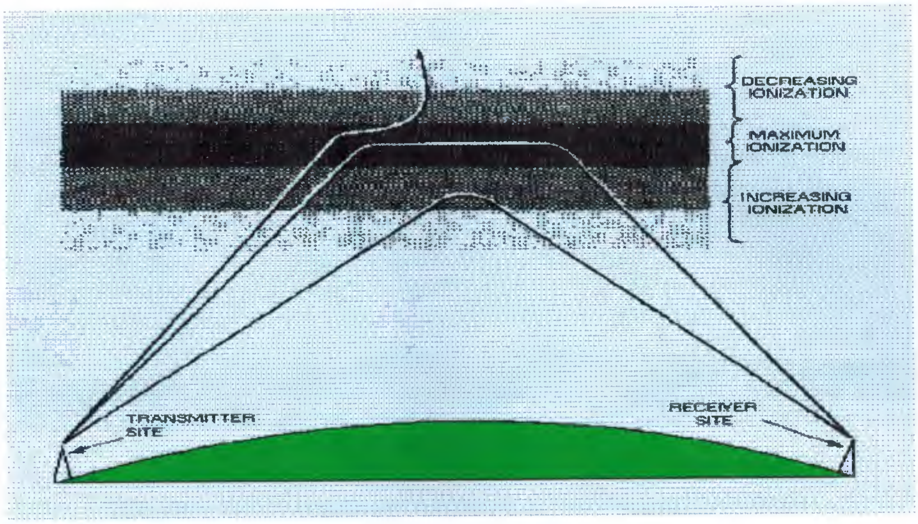


FIGURE 3.6 Effects of Ionospheric Density on Radio Waves.

If a wave strikes a thin, very highly ionized layer, the wave may be bent back so rapidly that it will appear to have been reflected instead of refracted back to Earth. To reflect a radio wave, the highly ionized layer must be approximately no thicker than one wavelength of the radio wave. Since the ionized layers are often several miles thick, ionospheric reflection is more likely to occur at long wavelengths (low frequencies).

Frequency. - For any given time, each ionospheric layer has a maximum frequency at which radio waves can be transmitted vertically and refracted back to Earth. This frequency is known as the CRITICAL FREQUENCY. It is a term that you will hear frequently in any discussion of radio wave propagation. Radio waves transmitted at frequencies higher than the critical frequency of a given layer will pass through the layer and be lost in space; but if these same waves enter an upper layer with a higher critical frequency, they will be refracted back to Earth. Radio waves of frequencies lower than the critical frequency will also be refracted back to Earth unless they are absorbed or have been refracted from a lower layer. The lower the frequency of a radio wave, the more rapidly the wave is refracted by a given degree of ionization. Figure 3-8 shows three separate waves of different frequencies entering an ionospheric layer at the same angle. Notice that the 5-megahertz wave is refracted quite sharply. The 20-megahertz wave is refracted less sharply and returned to Earth at a greater distance. The

100-megahertz wave is obviously greater than the critical frequency for that ionized layer and, therefore, is not refracted but is passed into space.

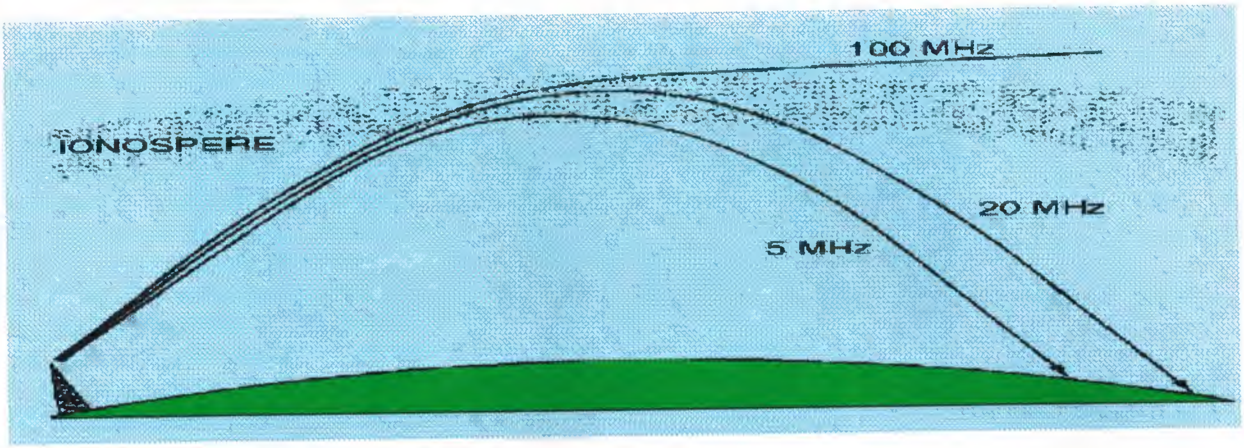


FIGURE 3.7 Frequency Versus Refraction and Distance

3.3 Angle of Incidence

The rate at which a wave of a given frequency is refracted by an ionized layer depends on the angle at which the wave enters the layer. Figure 3-9 shows three radio waves of the same frequency entering a layer at different angles. The angle at which wave a strikes the layer is too nearly vertical for the wave to be refracted to Earth. As the wave enters the layer, it is bent slightly but passes through the layer and is lost. When the wave is reduced to an angle that is less than vertical (wave B), it strikes the layer and is refracted back to Earth. The angle made by wave B is called the CRITICAL ANGLE for that particular frequency. Any wave that leaves the antenna at an angle greater than the critical angle will penetrate the ionospheric layer for that frequency and then be lost in space. Wave C strikes the ionosphere at the smallest angle at which the wave can be refracted and still return to Earth. At any smaller angle, the wave will be refracted but will not return to Earth.

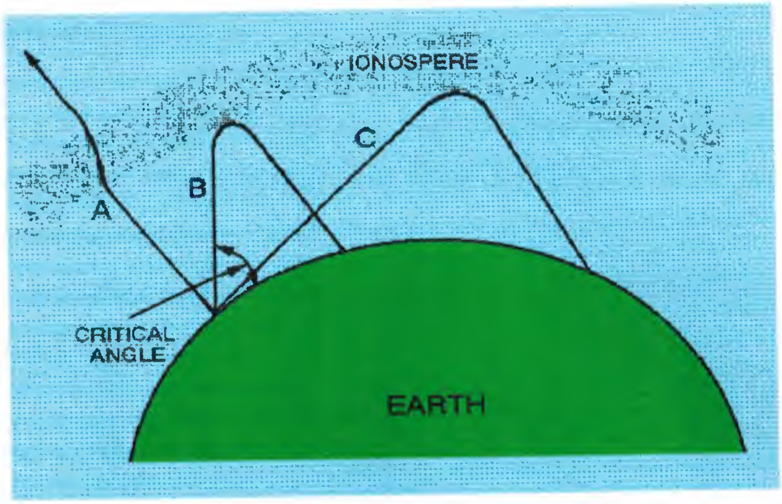


FIGURE 3.8 Different Incident Angles of Radio Waves.

As the frequency of the radio wave is increased, the critical angle must be reduced for refraction to occur. This is illustrated in figure 3-10. The 2-megahertz wave strikes the layer at the critical angle for that frequency and is refracted back to Earth. Although the 5-megahertz wave (broken line) strikes the ionosphere at a lesser angle, it nevertheless penetrates the layer and is lost. As the angle is lowered from the vertical, however, a critical angle for the 5-megahertz wave is reached, and the wave is then refracted to Earth.

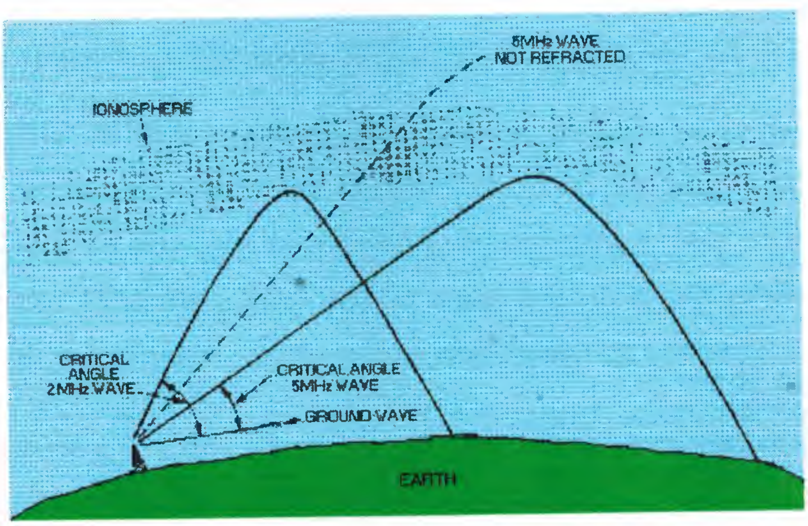


FIGURE 3.9 Effects of Frequency on the Critical Angle.

3.3.1 Skip Distance/Skip Zone

In figure 3.11, 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.

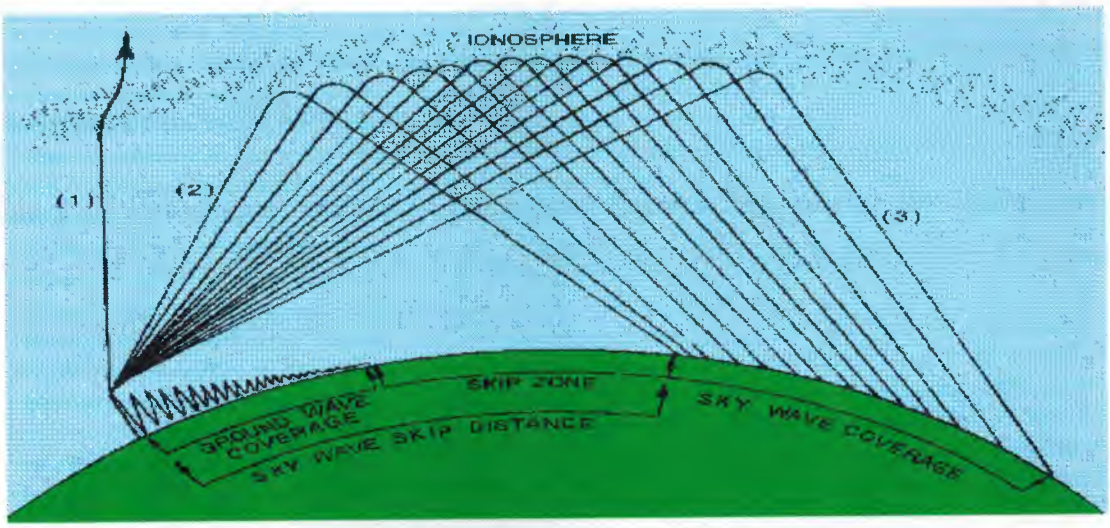


FIGURE 3.10 Relationship Between Skip Zones, Skip Distance, and Ground Wave.

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.

3.4 Propagation Path

The path that a refracted wave follows to the receiver depends on the angle at which the wave strikes the ionosphere. You should remember, however, that the rf energy radiated by a transmitting antenna spreads out with distance. The energy therefore strikes the ionosphere at many different angles rather than a single angle.

After the rf energy of a given frequency enters an ionospheric region, the paths that this energy might follow are many. It may reach the receiving antenna via two or more paths through a single layer. It may also, reach the receiving antenna over a path involving more than one layer, by multiple hops between the ionosphere and Earth, or by any combination of these paths.

Figure 3-12 shows how radio waves may reach a receiver via several paths through one layer. The various angles at which rf energy strikes the layer are represented by dark lines and designated as rays 1 through 6.

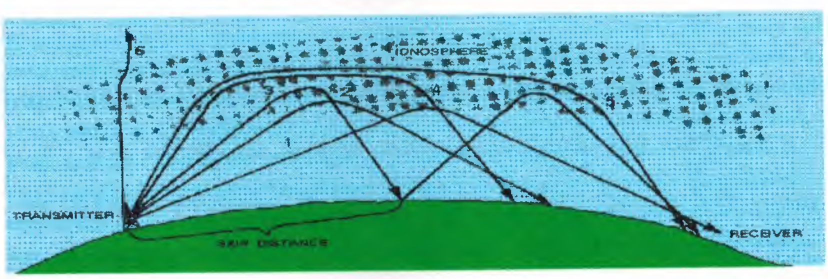


FIGURE 3.11 Ray Paths for A Fixed Frequency With Varying Angles of Incidence.

When the angle is relatively low with respect to the horizon (ray 1), there is only slight penetration of the layer and the propagation path is long. When the angle of incidence is increased (rays 2 and 3), the rays penetrate deeper into the layer but the range of these rays' decreases. When a certain angle is reached (ray 3), the penetration of the layer and rate of refraction are such that the ray is first returned to Earth at a minimal distance from the transmitter. Notice, however, that ray 3 still manages to reach the receiving site on its second refraction (called a hop) from the ionospheric layer.

As the angle is increased still more (rays 4 and 5), the rf energy penetrates the central area of maximum ionization of the layer. These rays are refracted rather slowly and are eventually returned to Earth at great distances. As the angle approaches vertical incidence (ray 6), the ray is not returned at all, but passes on through the layer.

3.5 Absorption in The Ionosphere

Many factors affect a radio wave in its path between the transmitting and receiving sites. The factor that has the greatest adverse effect on radio waves is ABSORPTION. Absorption results in the loss of energy of a radio wave and has a pronounced effect on both the strength of received signals and the ability to communicate over long distances.

You learned earlier in the section on ground waves that surface waves suffer most of their absorption losses because of ground-induced voltage. Sky waves, on the other hand, suffer most of their absorption losses because of conditions in the ionosphere. Note that some absorption of sky waves may also occur at lower atmospheric levels because of the presence of water and water vapor. However, this becomes important only at frequencies above 10,000 megahertz.

Most ionospheric absorption occurs in the lower regions of the ionosphere where ionization density is greatest. As a radio wave passes into the ionosphere, it loses some of its energy to the free electrons and ions. If these high-energy free electrons and ions do not collide with gas molecules of low energy, most of the energy lost by the radio wave is reconverted into electromagnetic energy, and the wave continues to be propagated with little change in intensity. However, if the high-energy free electrons and ions do collide with other particles, much of this energy is lost, resulting in absorption of the energy from the wave. Since absorption of energy depends on collision of the particles, the greater the density of the ionized layer, the greater the probability of collisions; therefore, the greater the absorption. The highly dense D and E layers provide the greatest absorption of radio waves.

Because the amount of absorption of the sky wave depends on the density of the ionosphere, which varies with seasonal and daily conditions, it is impossible to express a fixed relationship between distance and signal strength for ionospheric propagation. Under certain conditions, the absorption of energy is so great that communicating over any distance beyond the line of sight is difficult.

3.5.1 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 multipaths propagation.

3.5.2 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 3-13 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.

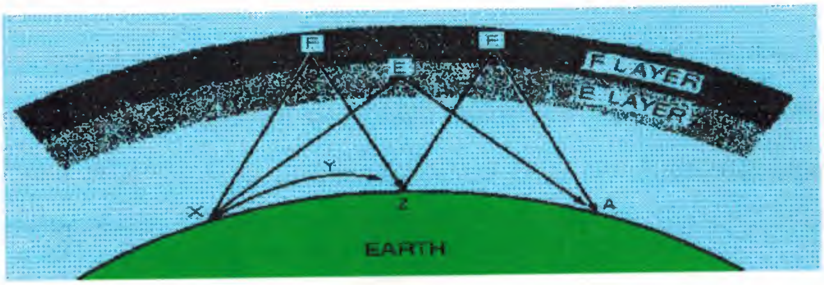


FIGURE 3.12 Multipaths Transmission

Multipaths 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.

3.5.3 Selective Fading

Fading resulting from multipaths propagation is variable with frequency since each frequency arrives at the receiving point via a different radio path. When a wide band of frequencies is transmitted simultaneously, each frequency will vary in the amount of fading. This variation is called SELECTIVE FADING. When selective fading occurs, all frequencies of the transmitted signal do not retain their original phases and relative amplitudes. This fading causes severe distortion of the signal and limits the total signal transmitted.

3.6 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 freespace loss. The combined effects of absorption, ground reflection loss, and freespace loss account for most of the energy losses of radio transmissions propagated by the ionosphere.

3.6.1 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.

3.6.2 Freespace 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 3-14.

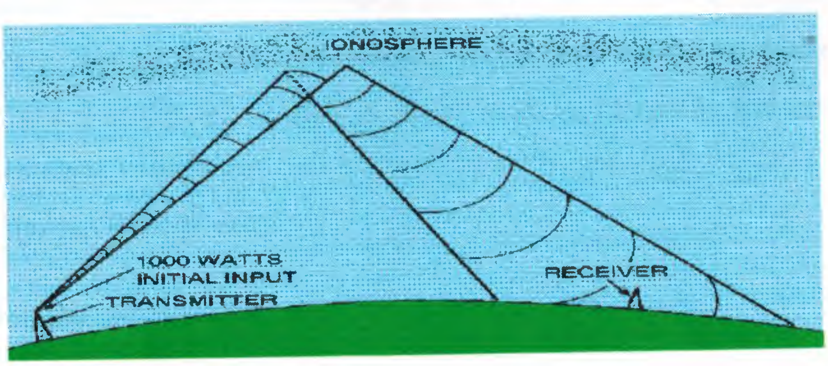


FIGURE 3.13 Freespace Loss Principle.

3.7 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.

3.7.1 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.

3.7.2 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.

3.7.3 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.

3.8 Variations in The Ionosphere

Because the existence of the ionosphere is directly related to radiations emitted from the sun, the movement of the Earth about the sun or changes in the sun's activity will result in variations in the ionosphere. These variations are of two general types: (1) those which are more or less regular and occur in cycles and, therefore, can be predicted in advance with reasonable accuracy, and (2) those which are irregular as a result of abnormal behavior of the sun and, therefore, cannot be predicted in advance. Both regular and irregular variations have important effects on radio wave propagation.

3.8.1 Regular Variations

The regular variations that affect the extent of ionization in the ionosphere can be divided into four main classes: daily, seasonal, 11-year, and 27-day variations.

DAILY. - Daily variations in the ionosphere are a result of the 24-hour rotation of the Earth about its axis. Daily variations of the different layers are summarized as follows:

The D layer reflects vlf waves; is important for long range vlf communications; refracts lf and mf waves for short range communications; absorbs hf waves; has little effect on vhf and above; and disappears at night. In the E layer, ionization depends on the angle of the sun. The E layer refracts hf waves during the day up to 20 megahertz to distances of about 1200 miles. Ionization is greatly reduced at night. Structure and density of the F region depend on the time of day and the angle of the sun. This region consists of one layer during the night and splits into two layers during daylight hours.

- Ionization density of the F1 layer depends on the angle of the sun.

- Its main effect is to absorb hf waves passing through to the F2 layer.

- The F2 layer is the most important layer for long distance hf communications.

It is a very variable layer and its height and density change with time of day, season, and sunspot activity.

SEASONAL. - Seasonal variations are the result of the Earth revolving around the sun; the relative position of the sun moves from one hemisphere to the other with changes in seasons. Seasonal variations of the D, E, and F1 layers correspond to the highest angle of the sun; thus the ionization density of these layers is greatest during the summer. The F2 layer, however, does not follow this pattern; its ionization is greatest in winter and least in summer, the reverse of what might be expected. As a result, operating frequencies for F2 layer propagation are higher in the winter than in the summer.

Eleven-Year Sun Spot Cycle. - One of the most notable phenomena on the surface of the sun is the appearance and disappearance of dark, irregularly shaped areas known as SUNSPOTS. The exact nature of sunspots is not known, but scientists believe they are caused by violent eruptions on the sun and are characterized by unusually strong magnetic fields. These sunspots are responsible for variations in the ionization level of the ionosphere. Sunspots can, of course, occur unexpectedly, and the life span of individual sunspots is variable; however, a regular cycle of sunspot activity has also been observed. This cycle has both a minimum and maximum level of sunspot activity that occur approximately every 11 years.

During periods of maximum sunspot activity, the ionization density of all layers increases. Because of this, absorption in the D layer increases and the critical frequencies for the E, F1, and F2 layers are higher. At these times, higher operating frequencies must be used for long distance communications.

27-Day Sunspot Cycle. - The number of sunspots in existence at any one time is continually subject to change as some disappear and new ones emerge. As the sun rotates on its own axis, these sunspots are visible at 27-day intervals, the approximate period required for the sun to make one complete rotation.

The 27-day sunspot cycle causes variations in the ionization density of the layers on a day-to-day basis. The fluctuations in the F2 layer are greater than for any other layer.

For this reason, precise predictions on a day-to-day basis of the critical frequency of the F2 layer are not possible. In calculating frequencies for long-distance communications, allowances for the fluctuations of the F2 layer must be made.

Irregular Variations . - Irregular variations in ionospheric conditions also have an important effect on radio wave propagation. Because these variations are irregular and unpredictable, they can drastically affect communications capabilities without any warning.

The more common irregular variations are sporadic E, sudden ionospheric disturbances, and ionospheric storms.

Sporadic E. - Irregular cloud-like patches of unusually high ionization, called sporadic E, often form at heights near the normal E layer. Exactly what causes this phenomenon is not known, nor can its occurrence be predicted. It is known to vary significantly with latitude, and in the northern latitudes, it appears to be closely related to the aurora borealis or northern lights.

At times the sporadic E is so thin that radio waves penetrate it easily and are returned to earth by the upper layers. At other times, it extends up to several hundred miles and is heavily ionized.

These characteristics may be either harmful or helpful to radio wave propagation. For example, sporadic E may blank out the use of higher, more favorable ionospheric layers or cause additional absorption of the radio wave at some frequencies. Also, it can cause additional multipath problems and delay the arrival times of the rays of rf energy.

On the other hand, the critical frequency of the sporadic E is very high and can be greater than double the critical frequency of the normal ionospheric layers. This condition may permit the long distance transmission of signals at unusually high frequencies. It may also permit short distance communications to locations that would normally be in the skip zone.

The sporadic E can form and disappear in a short time during either the day or night. However, it usually does not occur at the same time at all transmitting or receiving stations.

Sudden Ionospheric Disturbances. - The most startling of the ionospheric irregularities is known as a SUDDEN IONOSPHERIC DISTURBANCE (sid). These disturbances may occur without warning and may prevail for any length of time, from a few minutes to several hours. When sid occurs, long distance propagation of hf radio waves is almost totally "blanked out." The immediate effect is that radio operators listening on normal frequencies are inclined to believe their receivers have gone dead.

When sid has occurred, examination of the sun has revealed a bright solar eruption. All stations lying wholly, or in part, on the sunward side of the Earth are affected. The solar eruption produces an unusually intense burst of ultraviolet light, which is not absorbed by the F2, F1, and E layers, but instead causes a sudden abnormal increase in the ionization density of the D layer. As a result, frequencies above 1 or 2 megahertz are unable to penetrate the D layer and are usually completely absorbed by the layer.

Ionospheric Storms. - Ionospheric storms are disturbances in the Earth's magnetic field. They are associated, in a manner not fully understood, with both solar eruptions and the 27-day intervals, thus corresponding to the rotation of the sun.

Scientists believe that ionospheric storms result from particle radiation from the sun. Particles radiated from a solar eruption have a slower velocity than ultraviolet light waves produced by the eruption. This would account for the 18-hour or so time difference between a sid and an ionospheric storm. An ionospheric storm that is associated with sunspot activity may begin anytime from 2 days before an active sunspot crosses the central meridian of the sun until four days after it passes the central meridian. At times, however, active sunspots have crossed the central region of the sun without any ionospheric storms occurring. Conversely, ionospheric storms have occurred when there were no visible spots on the sun and no preceding sid. As you can see, some correlation between ionospheric storms, sid, and sunspot activity is possible, but there are no hard and fast rules. Ionospheric storms can occur suddenly without warning.

The most prominent effects of ionospheric storms are a turbulent ionosphere and very erratic sky wave propagation. Critical frequencies are lower than normal, particularly for the F2 layer. Ionospheric storms affect the higher F2 layer first, reducing its ion density. Lower layers are not appreciably affected by the storms unless the disturbance is great. The practical effect of ionospheric storms is that the range of frequencies that can be used for communications on a given circuit is much smaller than normal, and communications are possible only at the lower working frequencies.

CHAPTER 4

FREQUENCY SELECTION CONSIDERATIONS

4.1 Frequency Selection Considrations

Up to this point, we have covered various factors that control the propagation of radio waves through the ionosphere, such as the structure of the ionosphere, the incidence angle of radio waves, operating frequencies, etc. There is a very good reason for studying radio wave propagation. You must have a thorough knowledge of radio wave propagation to exercise good judgment when you select transmitting and receiving antennas and operating frequencies. Selection of a suitable operating frequency (within the bounds of frequency allocations and availability) is of prime importance in maintaining reliable communications.

For successful communications between any two specified locations at any given time of the day, there is a maximum frequency, a lowest frequency, and an optimum frequency that can be used.

4.1.1 Maximum Usable Frequency

As we discussed earlier, the higher the frequency of a radio wave, the lower the rate of refraction by an ionized layer. Therefore, for a given angle of incidence and time of day, there is a maximum frequency that can be used for communications between two given locations. This frequency is known as the MAXIMUM USABLE FREQUENCY (muf).

Waves at frequencies above the muf are normally refracted so slowly that they return to Earth beyond the desired location, or pass on through the ionosphere and are lost. You should understand, however, that use of an established muf certainly does not guarantee successful communications between a transmitting site and a receiving site. Variations in the ionosphere may occur at any time and consequently raise or lower the predetermined muf. This is particularly true for radio waves being refracted by the highly variable F2 layer.

The muf is highest around noon when ultraviolet light waves from the sun are the most intense. It then drops rather sharply as recombination begins to take place.

4.1.2 Lowest Usable Frequency

As there is a maximum operating frequency that can be used for communications between two points, there is also a minimum operating frequency. This is known as the LOWEST USABLE FREQUENCY (luf).

As the frequency of a radio wave is lowered, the rate of refraction increases. So a wave whose frequency is below the established luf is refracted back to Earth at a shorter distance than desired, as shown in figure 4-1.

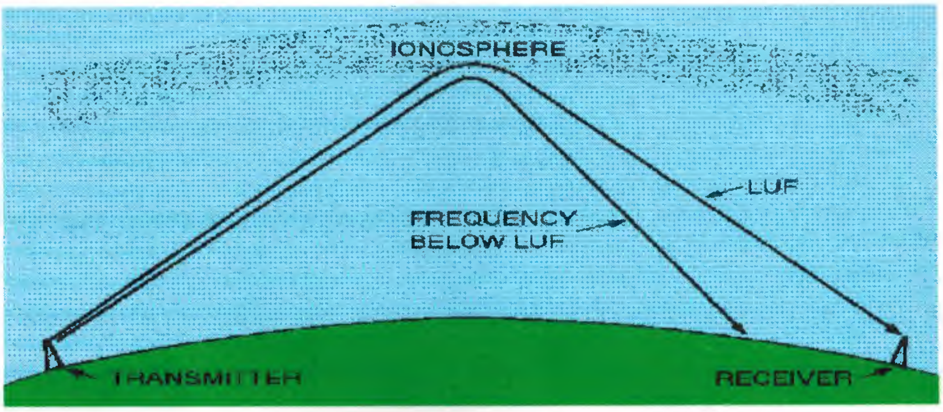


FIGURE 4.1 Refraction of Frequency Below the Lowest Usable Frequency (Luf).

The transmission path that results from the rate of refraction is not the only factor that determines the luf. As a frequency is lowered, absorption of the radio wave increases. A wave whose frequency is too low is absorbed to such an extent that it is too weak for reception. Likewise, atmospheric noise is greater at lower frequencies; thus, a low-frequency radio wave may have an unacceptable signal-to-noise ratio.

For a given angle of incidence and set of ionospheric conditions, the luf for successful communications between two locations depends on the refraction properties of the ionosphere, absorption considerations, and the amount of atmospheric noise present.

Optimum Working Frequency. -Neither the muf nor the luf is a practical operating frequency. While radio waves at the luf can be refracted back to Earth at the desired location, the signal-to-noise ratio is still much lower than at the higher frequencies, and the probability of multipath propagation is much greater. Operating at or near the muf can result in frequent signal fading and dropouts when ionospheric variations alter the length of the transmission path.

The most practical operating frequency is one that you can rely on with the least amount of problems. It should be high enough to avoid the problems of multipath, absorption, and noise encountered at the lower frequencies; but not so high as to result in the adverse effects of rapid changes in the ionosphere.

A frequency that meets the above criteria has been established and is known as the OPTIMUM WORKING FREQUENCY. It is abbreviated "fot"from the initial letters of the French words for optimum working frequency, "frequence optimum de travail." The fot is roughly about 85 percent of the muf but the actual percentage varies and may be either considerably more or less than 85 percent.

4.2 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.

4.2.1 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. 4-2). 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.

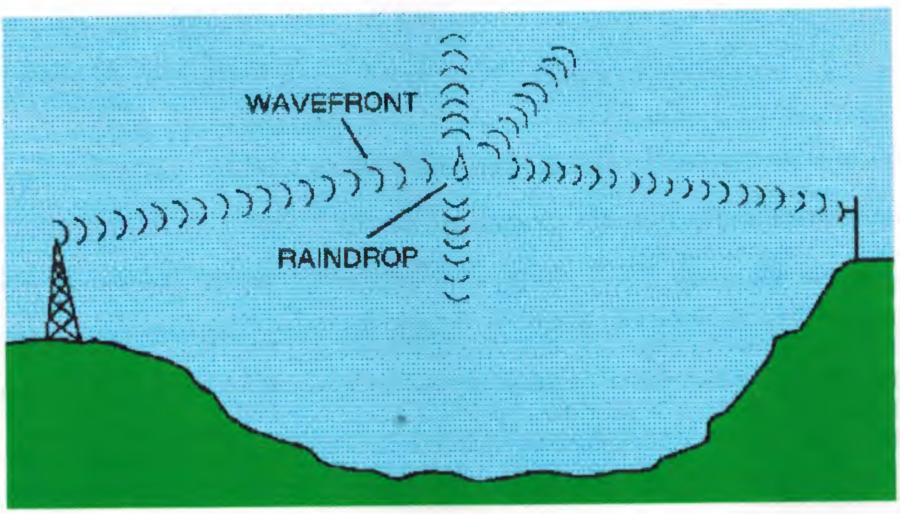


FIGURE 4.2 Rf Energy Losses from Scattering.

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.

4.2.2 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 4-3.

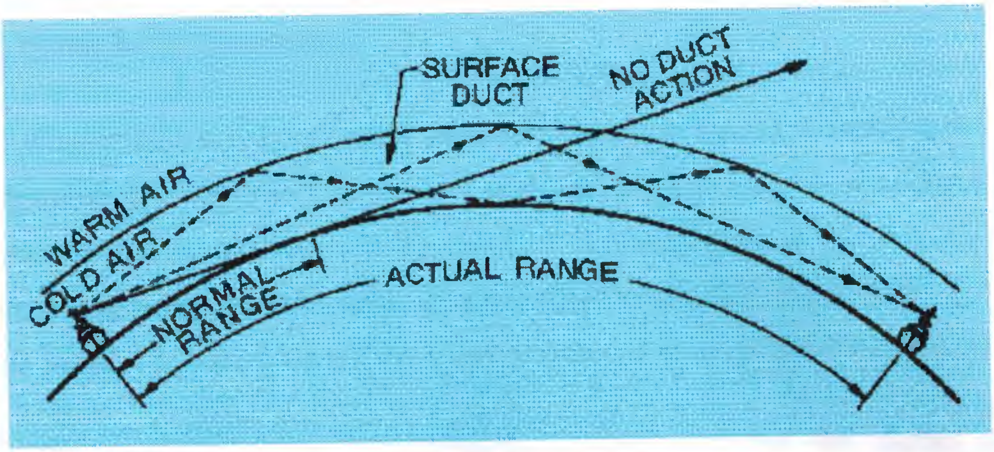


FIGURE 4.3 Duct Effect Caused By Temperature Inversion.

4.3 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.

4.4 Tropospheric Scattring

When a radio wave passing through the troposphere meets a turbulence, it makes an abrupt change in velocity. This causes a small amount of the energy to be scattered in a forward direction and returned to Earth at distances beyond the horizon. This phenomenon is repeated as the radio wave meets other turbulences in its path. The total received signal is an accumulation of the energy received from each of the turbulences.

This scattering mode of propagation enables vhf and uhf signals to be transmitted far beyond the normal line-of-sight. To better understand how these signals are transmitted over greater distances, you must first consider the propagation characteristics of the space wave used in vhf and uhf line-of-sight communications. When the space wave is transmitted, it undergoes very little attenuation within the line-of-sight horizon. When it reaches the horizon, the wave is diffracted and follows the Earth's curvature. Beyond the horizon, the rate of attenuation increases very rapidly and signals soon become very weak and unusable.

Tropospheric scattering, on the other hand, provides a usable signal at distances beyond the point where the diffracted space wave drops to an unusable level. This is because of the height at which scattering takes place. The turbulence that causes the scattering can be visualized as a relay station located above the horizon; it receives the transmitted energy and then reradiates it in a forward direction to some point beyond the line-of-sight distance. A high gain receiving antenna aimed toward this scattered energy can then capture it.

The magnitude of the received signal depends on the number of turbulences causing scatter in the desired direction and the gain of the receiving antenna. The scatter area used for tropospheric scatter is known as the *scatter volume*. The angle at which the receiving antenna must be aimed to capture the scattered energy is called the *scatter angle*. The scatter volume and scatter angle are shown in figure 4-4.

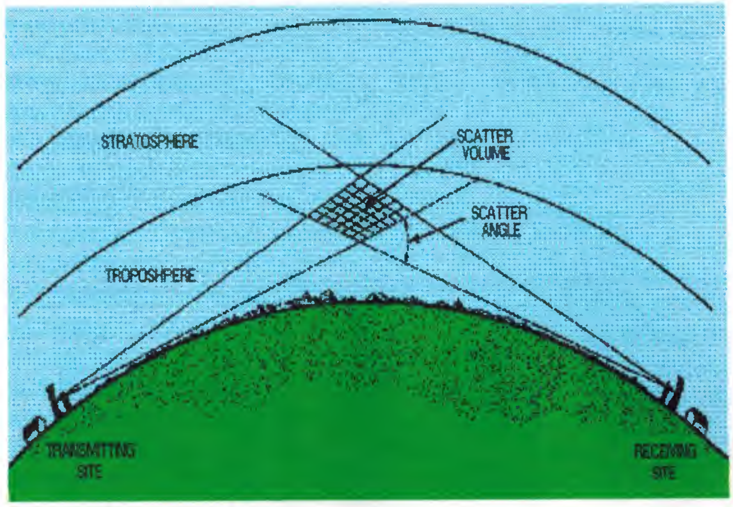


FIGURE 4.4 Tropospheric Scattering Propagation.

The signal take-off angle (transmitting antenna's angle of radiation) determines the height of the scatter volume and the size of the scatter angle. A low signal take-off angle produces a low scatter volume, which in turn permits a receiving antenna that is aimed at a low angle to the scatter volume to capture the scattered energy.

As the signal take-off angle is increased, the height of the scatter volume is increased. When this occurs, the amount of received energy decreases. There are two reasons for this: (1) scatter angle increases as the height of the scatter volume is increased; (2) the amount of turbulence decreases with height. As the distance between the transmitting and receiving antennas is increased, the height of the scatter volume must also be increased. The received signal level, therefore, decreases as circuit distance is increased.

The tropospheric region that contributes most strongly to tropospheric scatter propagation lies near the midpoint between the transmitting and receiving antennas and just above the radio horizon of the antennas.

Since tropospheric scatter depends on turbulence in the atmosphere, changes in atmospheric conditions have an effect on the strength of the received signal. Both daily and seasonal variations in signal strength occur as a result of changes in the atmosphere. These variations are called *long-term fading*.

In addition to long-term fading, the tropospheric scatter signal often is characterized by very rapid fading because of multipath propagation. Since the turbulent condition is constantly changing, the path lengths and individual signal levels are also changing, resulting in a rapidly changing signal. Although the signal level of the received signal is constantly changing, the average signal level is stable; therefore, no complete fade out occurs.

Another characteristic of a tropospheric scatter signal is its relatively low power level. Since very little of the scattered energy is reradiated toward the receiver, the efficiency is very low and the signal level at the final receiver point is low. Initial input power must be high to compensate for the low efficiency in the scatter volume. This is accomplished by using high-power transmitters and high-gain antennas, which concentrate the transmitted power into a beam, thus increasing the intensity of energy of each turbulence in the volume. The receiver must also be very sensitive to detect the low-level signals.

4.4.1 Application of Tropospheric Scattering

Tropospheric scatter propagation is used for point-to-point communications. A correctly designed tropospheric scatter circuit will provide highly reliable service for distances ranging from 50 miles to 500 miles. Tropospheric scatter systems may be particularly useful for communications to locations in rugged terrain that are difficult to reach with other methods of propagation. One reason for this is that the tropospheric scatter circuit is not affected by ionospheric and auroral disturbances.

CHAPTER 5

VHF/UHF/MICROWAVE RADIO PROPAGATION

5.1 Estimating Path Loss

The fundamental aim of a radio link is to deliver sufficient signal power to the receiver at the far end of the link to achieve some performance objective. For a data transmission system, this objective is usually specified as a minimum bit error rate (BER). In the receiver demodulator, the BER is a function of the signal to noise ratio (SNR). At the frequencies under consideration here, the noise power is often dominated by the internal receiver noise; however, this is not always the case, especially at the lower (VHF) end of the range. In addition, the "noise" may also include significant power from interfering signals, necessitating the delivery of higher signal power to the receiver than would be the case under more ideal circumstances (i.e., back-to-back through an attenuator). If the channel contains multipath, this may also have a major impact on the BER. We will consider multipath in more detail later - for now, we will focus on predicting the signal power which will be available to the receiver.

5.2.1 Free Space Propagation

The benchmark by which we measure the loss in a transmission link is the loss that would be expected in free space - in other words, the loss that would occur in a region which is free of all objects that might absorb or reflect radio energy. This represents the ideal case which we hope to approach in our real world radio link (in fact, it is possible to have path loss which is less than the "free space" case, as we shall see later, but it is far more common to fall short of this goal).

Calculating free space transmission loss is quite simple. Consider a transmitter with power P_t coupled to an antenna which radiates equally in all directions (everyone's favorite mythical antenna, the *isotropic* antenna). At a distance d from the transmitter, the radiated power is distributed uniformly over an area of $4\pi d^2$ (i.e. the surface area of a sphere of radius d), so that the *power flux density* is:

$$s = \frac{P_t}{4\pi d^2} \quad (1)$$

The transmission loss then depends on how much of this power is captured by the receiving antenna. If the capture area, or *effective aperture* of this antenna is A_r, then the power which can be delivered to the receiver (assuming no mismatch or feedline losses) is simply

$$P_r = sA_r \quad (2)$$

For the hypothetical isotropic receiving antenna, we have

$$A_r = \frac{\lambda^2}{4\pi} \quad (3)$$

Combining equations (1) and (3) into (2), we have

$$P_r = P_t\left(\frac{\lambda}{4\pi d}\right)^2 \quad (4)$$

The free space path loss between isotropic antennas is P_t / P_r. Since we usually are dealing with frequency rather than wavelength, we can make the substitution = c/f (where c, of course, is the speed of light) to get

$$L_p = \left(\frac{4\pi}{c}\right)^2 f^2 d^2 \quad (5)$$

This shows the classic square-law dependence of signal level versus distance. What troubles some people when they see this equation is that the path loss also increases as the square of the frequency. Does this mean that the transmission medium is inherently more lossy at higher frequencies? While it is true that absorption of RF by various materials (buildings, trees, water vapor, etc.) tends to increase with frequency, remember we are talking about "free space" here. The frequency dependence in this case is solely due to the decreasing effective aperture of the receiving antenna as the frequency increases. This is intuitively reasonable, since the physical size of a given antenna type is inversely proportional to frequency. If we double the frequency, the linear dimensions of the antenna decrease by a factor of one-half, and the capture area by a factor of one-quarter. The antenna therefore captures only one-quarter of the power flux density at the higher frequency versus the lower one, and delivers 6 dB less signal to the receiver. However, in most cases we can easily get this 6 dB back by increasing the effective aperture, and hence the gain, of the receiving antenna. For example, suppose we are using a parabolic dish antenna at the lower frequency. When we double the frequency, instead of allowing the dish to be scaled down in size so as to produce the same gain as before, we can maintain the same reflector size.This gives us the same effective aperture as before (assuming that the feed is properly redesigned for the new frequency, etc.), and 6 dB more gain (remembering that the gain is with respect to an isotropic or dipole reference antenna at the *same frequency*). Thus the free space path loss is now the same at both frequencies; moreover, if we maintained the same physical aperture at *both* ends of the link, we would actually have 6 dB *less* path loss at the higher frequency. You can picture this in terms of being able to focus the energy more tightly at the frequency with the shorter wavelength. It has the added benefit of providing greater discrimination against multipath - more about this later.The free space path loss equation is more usefully expressed logarithmically:

$$L_p = 32.4 + 20\log f + 20\log d \;\; dB \quad \text{(f in MHz, d in km) (6a)}$$

or

$$L_p = 36.6 + 20\log f + 20\log d \;\; dB \quad \text{(f in MHz, d in miles) (6b)}$$

This shows more clearly the relationship between path loss and distance: path loss increases by 20 dB/decade or 6 dB/octave, so each time you double the distance, you lose another 6 dB of signal under free space conditions.

Of course, in looking at a real system, we must consider the actual antenna gains and cable losses in calculating the signal power P_r which is available at the receiver input:

$$P_r = P_t - L_p + G_t + G_r - L_t - L_r \quad (7)$$

where

P_t = transmitter power output (dBm or dBW, same units as P_r)

L_p = free space path loss between isotropic antennas (dB)

G_t = transmit antenna gain (dBi)

G_r = receive antenna gain (dBi)

L_t = transmission line loss between transmitter and transmit antenna (dB)

L_r = transmission line loss between receive antenna and receiver input (dB)

A table of transmission line losses for various bands and popular cable types can be found in the Appendix.

Example 1. Suppose you have a pair of 915 MHz WaveLAN cards, and want to use them on a 10 km link on which you believe free space path loss conditions will apply. The transmitter power is 0.25 W, or +24 dBm. You also have a pair of yagi antennas with 10 dBi gain, and at each end of the link, you need about 50 ft (15 m) of transmission line to the antenna. Let's say you're using LMR-400 coaxial cable, which will give you about 2 dB loss at 915 MHz for each run. Finally, the path loss from equation (6a) is calculated, and this gives 111.6 dB, which we'll round off to 112 dB. The expected signal power at the receiver is then, from (7):

$$P_r = 24 - 112 + 10 + 10 - 2 - 2 = -72 \ dBm$$

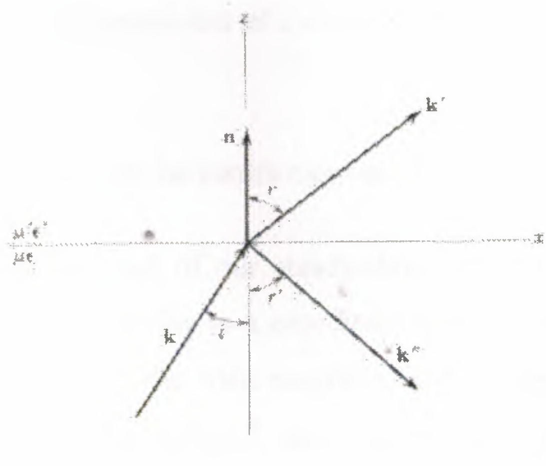
According to the WaveLAN specifications, the receivers require -78 dBm signal level in order to deliver a low bit error rate (BER). So, we should be in good shape, as we have 6 dB of margin over the minimum requirement. However, this will only be true *if* the path really is equivalent to the free space case, and this is a big *if*! We'll look at means of predicting whether the free space assumption holds in the next section.

5.1.2 Simplified Model of Propagation in the Ionosphere

The simplest approach to describing radio wave propagation is to solve for the index of refraction $\eta = (\mu\ \varepsilon)^{1/2}$, where μ = magnetic permeability **(1.25664×10^{-6} H m^{-1})** and ε = dielectric constant. The index of refraction, in turn, describes the relationship between the angles of incidence and refraction through Snell's Law

$$\text{Sin i} / \text{Sin r} = \eta' / \eta.$$

This is shown graphically in the figure below which shows an incident wave k striking a plane interface between different media, giving rise to a reflected wave k'' and a refracted wave k'.



Figuer 4.5 k and k` axis's

Since the magnetic permeability is constant in the ionosphere, our goal is to now solve for the dielectric constant from the Equation of Motion, where the dielectric constant is defined as the ratio of the strength of an electric field in a vacuum to that in the ionosphere.

We now consider a simple problem of a tenuous electron plasma of uniform density trapped in a strong, static, and uniform magnetic induction Bo. If we assume that the transverse radio waves propagate parallel to Bo, the Equation of Motion for electrons trapped in this ionospheric plasma is given by

$$\mathbf{m\ \delta^2 x/\delta t^2 - e/c\ Bo\ X\ \delta x/\delta t = -e\ E\ e^{-i\omega t}},$$

where the influence of the **B** field of the transverse wave has been neglected compared to the static induction **Bo** and the electron charge is given by **-e**. It is now customary to describe the electric field component of the radio waves as circularly polarized which implies

$$\mathbf{E = (\varepsilon_1 \pm i\varepsilon_2)\ E}$$

and a similar expression for **x.** Since **Bo** is orthogonal to both ε_1 and ε_2, the cross product in our Equation of Motion has components only in the directions ε_1 and ε_2; therefore, the transverse components decouple. This leads to a steady-state solution given by

$$\mathbf{x = e\ E\ /\ m\ \omega\ (\omega \mp \omega_B)},$$

where ω_B is the frequency of precession of a charged particle in a magnetic field which is given by

$\mathbf{\omega_B = e\ Bo\ /\ mc \sim 6 \times 10^6\ sec^{-1}}$ (in the earth's magnetic field of **Bo=0.3** gauss).

The frequency dependence of our steady-state solution can be determined by transforming our Equation of Motion to a coordinate system precessing with frequency ω_B about the direction of **Bo**. If the static magnetic field is neglected, the force on the electrons has an effective frequency **($\omega \pm \omega_B$)**, depending on the sign of the circular polarization.

The steady-state solution implies a dipole moment for each electron and yields, for a bulk sample, the dielectric constant of the ionosphere

$$\mathbf{\varepsilon_{\mp} = 1 - \{\omega_p^2\ /\ \omega(\omega \mp \omega_B)\}},$$

where the upper sign corresponds to a positive helicity wave (left-handed circular polarization in optics notation), while the lower sign corresponds to negative helicity. Furthermore, ω is the frequency of our radio wave of interest and ω_p is the plasma frequency of the ionosphere and it is given by

$$\omega_p^2 = 4\pi\, NZ\, e^2 / m ,$$

where **NZ** is the density of electrons per unit volume. For propagation antiparallel to the magnetic field **Bo**, the signs are reversed. Furthermore, for propagation in directions other than (anti)parallel to the static field **Bo**, it is straight forward to show that, if terms of order ω_B^2 are neglected compared to ω^2 and $\omega\omega_B$, the dielectric constant is still given by ε_{-+} above.

In this simplified problem of ionospheric radio wave propagation, we see the essential characteristic that waves of right-handed and left-handed circular polarizations propagate differently. In other words, the ionosphere has both birefringent and anisotropic scattering properties.

For the earth's ionosphere, the density of free electrons ranges between $\mathbf{10^4}$ and $\mathbf{10^6}$ **electrons/cm^3**, corresponding to a plasma frequency on the order of $\omega_p \sim \mathbf{6x10^6}$ - $\mathbf{6x10^7}$ **sec^{-1}**. This along with the precession frequency ω_B given above implies a wide interval in frequency within the HF spectrum where one state of circular polarization cannot propagate within the medium at all; rather, this wave is totally reflected back towards the earth. The other state of polarization is partially transmitted. Thus, when a linearly polarized wave is incident on a plasma, the reflected wave will be elliptically polarized, with its major axis generally rotated away from the direction of polarization of the incident wave.

The propagation of HF radio waves off the ionosphere is explicable in terms of these ideas, but the presence of several layers of plasma with densities and relative positions varying with height and time makes this problem considerably more complicated than this simplified model implies. Therefore, most ionospheric research groups seek to understand the variation of electron density versus vertical height above the earth's surface. The electron densities at various heights can be inferred by studying the reflection of radio pulses transmitted vertically upwards (known as ionograms).

Such studies have shown that the number n_0 of free electrons per unit volume slowly increases with height within a given layer of the ionosphere where it reaches a maximum before falling off abruptly with further increases in height as shown in the figure below.

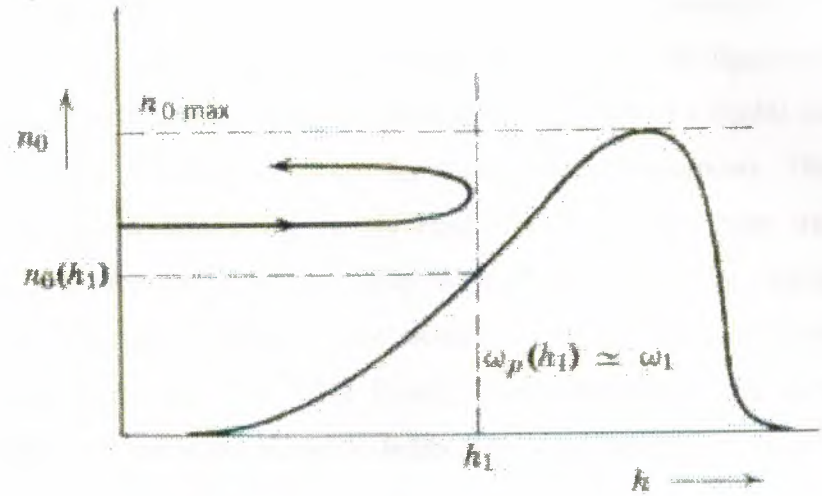


Figure 4.5 The Relish In ω

A pulse of given frequency ω_1 enters a layer without reflection because of the slow change in $\mathbf{n_0}$. When the density $\mathbf{n_0}$ is large enough, $\omega_p(h_1) \sim \omega_1$. At this point, the dielectric constant vanishes and the pulse is reflected vertically back to the earth. The electron density **NZ** required to induce this vertical reflection for a pulse of frequency ω is found by combining the equations above to give

$$\mathbf{NZ = (m / 4\pi e^2)\,(\omega^2 \mp \omega\omega_B).}$$

By measuring the time interval between the initial transmission and reception of the reflected signal, the height $\mathbf{h_1}$ corresponding to this electron density can be found. Therefore, by varying the frequency ω_1 and studying the change in time intervals (ionograms), the electron density as a function of height can be determined. If the frequency ω_1 is too high, the index of refraction remains finite and no vertical reflection occurs. Therefore, the maximum frequency at which the vertical reflections disappear determines the maximum electron density in a given ionospheric layer.

Unfortunately, vertical reflections typically disappear at frequencies higher than the 40m-30m range so that the more popular HF DX bands (10m-20m) cannot be adequately characterized by these vertical ionograms. For these higher frequencies, oblique ionograms are generally utilized to yield empiric data on the refractive properties of the ionosphere and the virtual altitudes of these reflections. However, such data are generally limited since the goal of most ionospheric research studies are aimed at determining the variation of electron density with height. The figure below illustrates the minimum ground distance needed (blind zone) to establish a digital communications link via reflection off the ionosphere for these higher frequencies. These data were recently obtained by connecting to my Nashville, TN pactor base station from my mobile pactor station during a trip to Key West, Florida. The data clearly show that as the frequency increases, the blind zone increases with no vertical reflections occurring at frequencies higher than ~7.5 MHz. Finally, these tests were made during a period of high solar flux and stable geomagnetic fields. The solar indices are shown on the top of the figure.

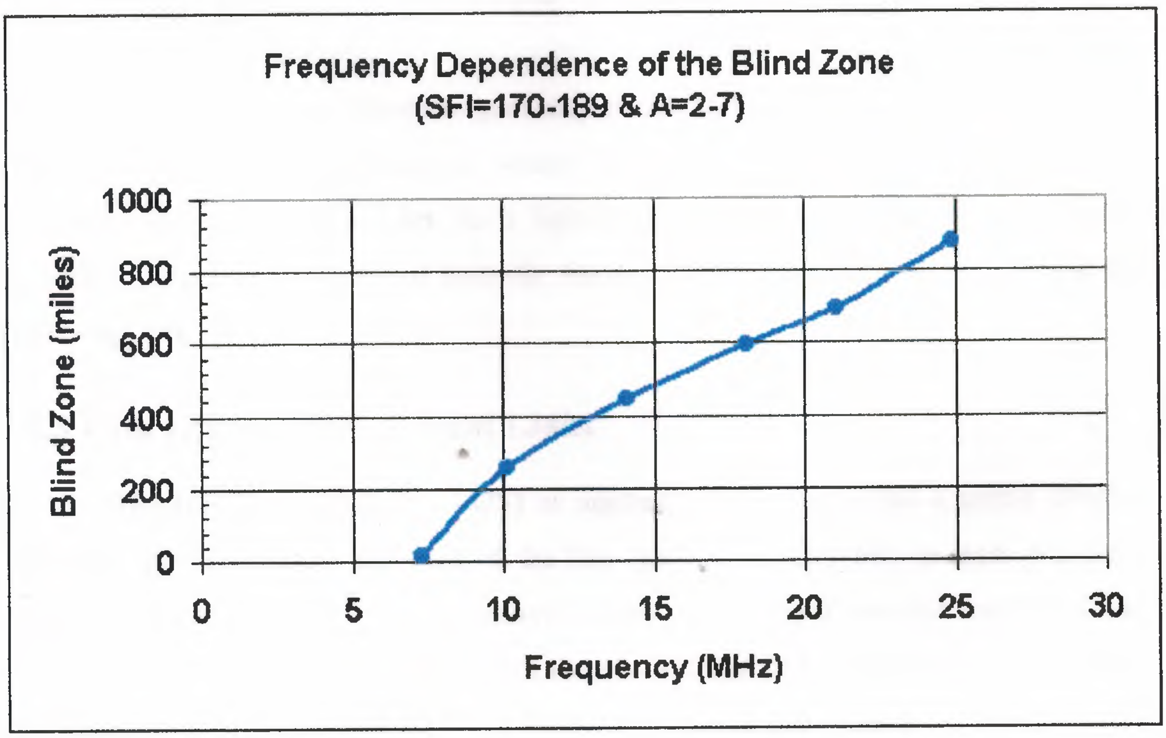


Figure 4.4 Frequency And Blind Zone

Whistlers

The frequency dependence of the dielectric constant $\varepsilon_-(\omega)$ at low frequencies is responsible for a peculiar magnetospheric propagation phenomenon known as "whistlers". As $\omega \to 0$, $\varepsilon_-(\omega)$ tends to positive infinity as $\varepsilon_- \sim \omega_p^2/\omega\omega_B$. Propagation occurs, but with a wave number

$$k\_ \sim (\omega_p/c)\{\omega/\omega_B\}^{1/2} .$$

This corresponds to a highly dispersive medium. Recalling that energy transport is governed by the group velocity $v_g=[d\omega/dk]_0$ leads to a solution for the group velocity in the magnetosphere at the MF range as

$$v_g(\omega) \sim 2v_p(\omega) \sim 2c\{(\omega\omega_B)^{1/2}/\omega_p\} .$$

This equation indicates that pulses of radiation at different frequencies travel at different speeds, in particular, the lower the frequency, the slower the speed. Whistlers occur when thunderstorms in one hemisphere generates a wide spectrum of frequencies, some of which propagate along the dipole lines of the earth's magnetic field described above with the higher frequency components reaching the antipodal point first and the lower ones later. These whistlers generally occur at frequencies below 100kHz and when received by a radio receiver sound like a whistle dropping in frequency. By assuming a distance of 10^4 km to a lightening discharge, the time scale for these whistlers occurs on the order of seconds. An example of a whistler can be heard at the following link: Whistler.wav file.

5.3 Path Loss on Line of Sight Links

The term Line of Sight (LOS) as applied to radio links has a pretty obvious meaning: the antennas at the ends of the link can "see" each other, at least in a radio sense. In many cases, radio LOS equates to optical LOS: you're at the location of the antenna at one end of the link, and with the unaided eye or binoculars, you can see the antenna (or its future site) at the other end of the link. In other cases, we may still have an LOS path even though we can't see the other end visually. This is because the radio horizon extends beyond the optical horizon. Radio waves follow slightly curved paths in the atmosphere, but if there is a direct path between the antennas which doesn't pass through any obstacles, then we still have radio LOS. Does having LOS mean that the path loss will be equal to the free space case which we have just considered? In some cases, the answer is yes, but it is definitely not a sure thing. There are three mechanisms which may cause the path loss to differ from the free space case:

- *refraction* in the earth's atmosphere, which alters the trajectory of radio waves, and which can change with time.

- *diffraction* effects resulting from objects near the direct path.

- *reflections* from objects, which may be either near or far from the direct path.

We examine these mechanisms in the next three sections.

5.3.1 Atmospheric Refraction

As mentioned previously, radio waves near the earth's surface do not usually propagate in precisely straight lines, but follow slightly curved paths. The reason is well-known to VHF/UHF DXers: refraction in the earth's atmosphere. Under normal circumstances, the index of refraction decreases monotonically with increasing height, which causes the radio waves emanating from the transmitter to bend slightly downwards towards the earth's surface instead of following a straight line. The effect is more pronounced at radio frequencies than at the wavelength of visible light, and the result is that the radio waves can propagate beyond the optical horizon, with no additional loss other than the free space distance loss.

There is a convenient artifice which is used to account for this phenomenon: when the path profile is plotted, we reduce the curvature of the earth's surface. If we choose the curvature properly, the paths of the radio waves can be plotted as straight lines. Under normal conditions, the gradient in refractivity index is such that real world propagation is equivalent to straight-line propagation over an earth whose radius is greater than the real one by a factor of 4/3 - thus the often-heard term "4/3 earth radius" in discussions of terrestrial propagation. However, this is just an approximation that applies under typical conditions - as VHF/UHF experimenters well know, unusual weather conditions can change the refractivity profile dramatically. This can lead to several different conditions. In *superrefraction*, the rays bend more than normal and the radio horizon is extended; in extreme cases, it leads to the phenomenon known as *ducting*, where the signal can propagate over enormous distances beyond the normal horizon. This is exciting for DXers, but of little practical use for people who want to run data links. The main consequence for digital experimenters is that they may occasionally experience interference from unexpected sources.

A more serious concern is *subrefraction*, in which the bending of the rays is less than normal, thus shortening the radio horizon and reducing the clearance over obstacles along the path. This may lead to increased path loss, and possibly even an outage. In commercial radio link planning, the statistical probability of these events is calculated and allowed for in the link design (distance, path clearance, fading margin, etc.). We won't get into all of the details here; suffice it to say that reliability of your link will tend to be higher if you back off the distance from the maximum which is dictated by the normal radio horizon. Not that you shouldn't try and stretch the limits when the need arises, but a link which has optical clearance is preferable to one which doesn't. It's also a good idea to build in some margin to allow for fading due to unusual propagation situations, and to allow as much clearance from obstacles along the path as possible. For short-range links, the effects of refraction can usually be ignored.

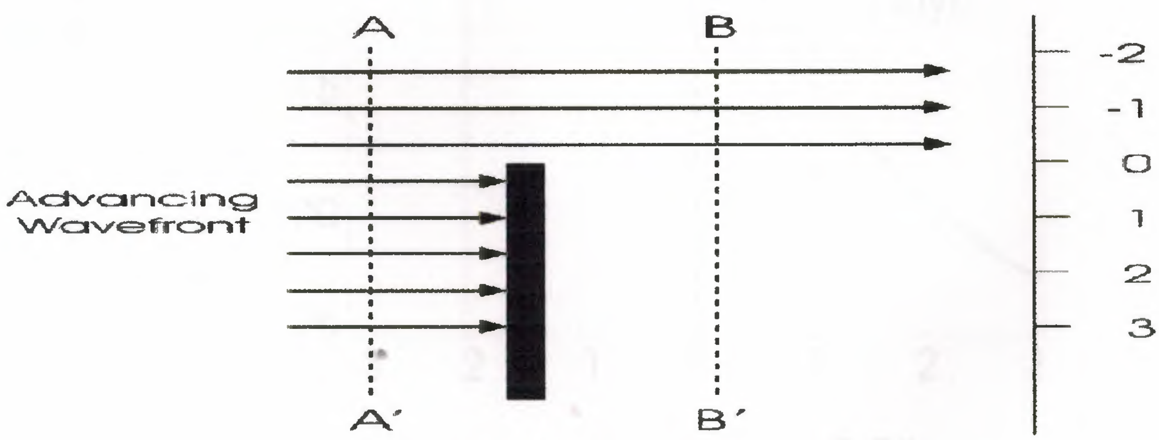


FIGURE 5.1 Shadowing of Radio Waves By an Object

5.3.2 Diffraction and Fresnel Zones

Refraction and reflection of radio waves are mechanisms which are fairly easy to picture, but diffraction is much less intuitive. To understand diffraction, and radio propagation in general, it is very helpful to have some feeling for how radio waves behave in an environment which is not strictly "free space". Consider Fig. 1, in which a wavefront is traveling from left to right, and encountering an obstacle which absorbs or reflects all of the incident radio energy. Assume that the incident wavefront is uniform; i.e., if we measure the field strength along the line A-A', it is the same at all points. Now, what will be the field strength along a line B-B' on the other side of the obstacle? To quantify this, we provide an axis in which zero coincides with the top of the obstacle, and negative and positive numbers denote positions above and below this, respectively (we'll define the parameter used on this axis a bit later).

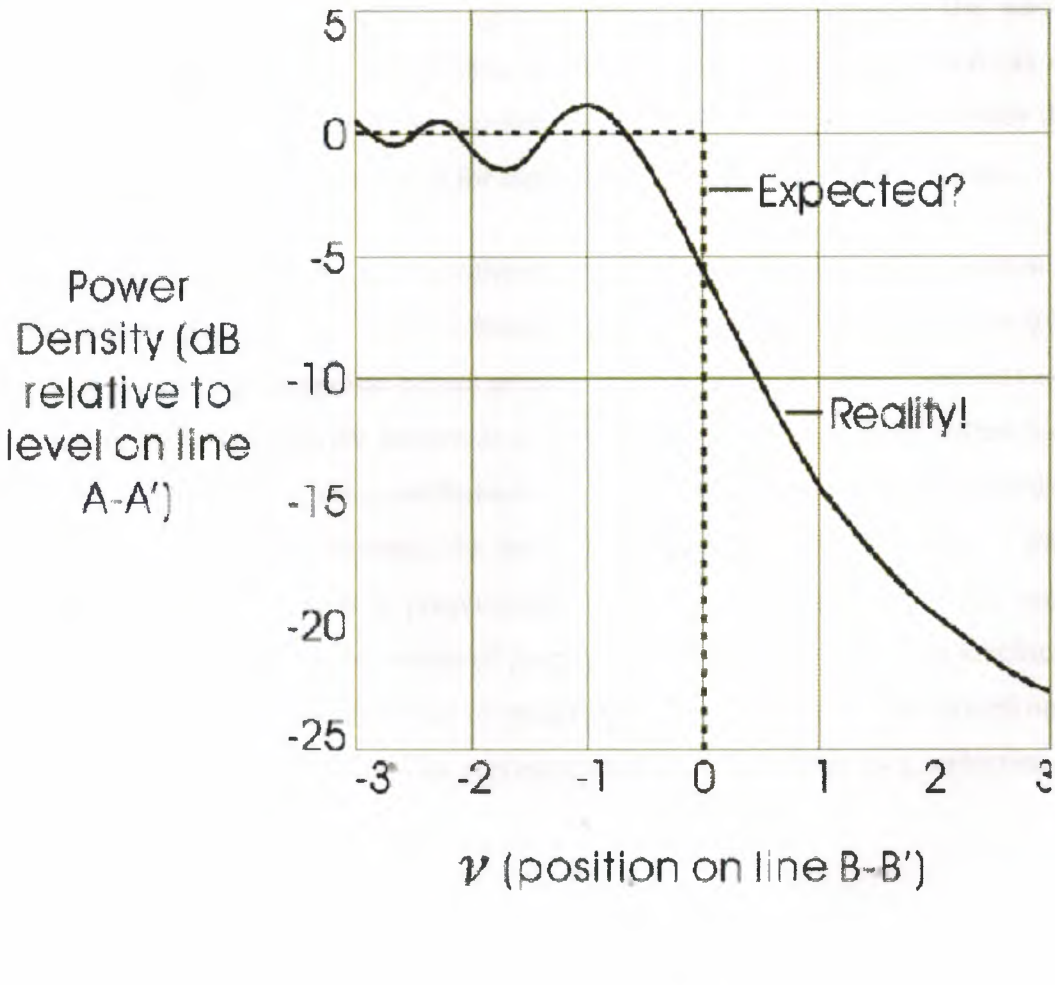


FIGURE 5.2 Signal Levels on the Far Side of the Shadowing Object

Intuition may lead one to expect the field strength along B-B' to look like the dashed line in Fig. 2, with complete shadowing and zero signal below the top of the obstacle, and no effect at all above it. The solid line shows the reality: not only does energy "leak" into the shadowed area, but the field strength above the top of the obstacle is also disturbed. At a position which is level with the top of the obstacle, the signal power density is down by some 6 dB, despite the fact that this point is in "line of sight" of the source. This effect is less surprising when one considers other familiar instances of wave motion. Picture, for example, tossing a rock in a pond and watching the ripples propagate outward.

When they encounter an object such as a boat or a pier, you will see that the water behind the object is also disturbed, and that the waves traveling past, but close to, the object are also affected somewhat. Similarly, consider a distant source of sound waves: if the sound level is well above the ambient level, then moving behind an object which absorbs the incident sound energy completely does not result in the sound disappearing completely - it is still audible at a lower level, due to diffraction (as an aside, it is interesting to note that the wavelength of a 1 KHz sound wave is nearly the same as a 1 GHz radio wave). So much for analogies - let's get back to radio waves.

The explanation for the non-intuitive behavior of radio waves in the presence of obstacles which appear in their path is found in something called *Huygens' Principle*. Huygens showed that propagation occurs as follows: each point on a wavefront acts as a source of a secondary wavefront known as a *wavelet*, and a new wavefront is then built up from the combination of the contributions from all of the wavelets on the preceding wavefront. The secondary wavelets do not radiate equally in all directions - their amplitude in a given direction is proportional to $(1 + \cos a)$, where a is the angle between that direction and the direction of propagation of the wavefront. The amplitude is therefore maximum in the direction of propagation (i.e., normal to the wavefront), and zero in the reverse direction. The representation of a wavefront as a collection of wavelets is shown in Fig. 3.

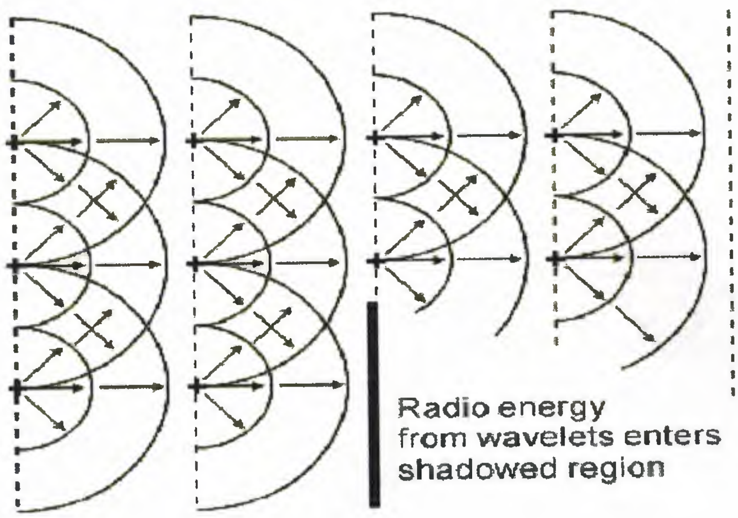


FIGURE 5.3 Representation of Radio Waves as Wavelets

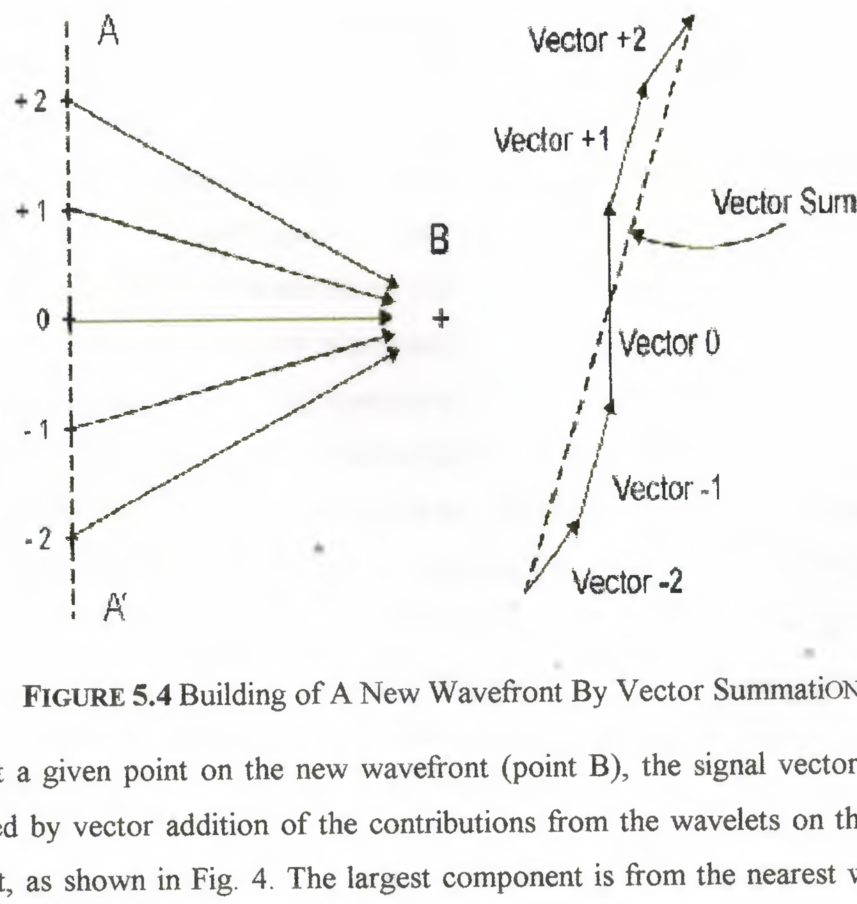


FIGURE 5.4 Building of A New Wavefront By Vector SummatiON

At a given point on the new wavefront (point B), the signal vector (phasor) is determined by vector addition of the contributions from the wavelets on the preceding wavefront, as shown in Fig. 4. The largest component is from the nearest wavelet, and we then get symmetrical contributions from the points above and below it. These latter vectors are shorter, due to the angular reduction of amplitude mentioned above, and also the greater distance traveled. The greater distance also introduces more time delay, and hence the rotation of the vectors as shown in the figure. As we include contributions from points farther and farther away, the corresponding vectors continue to rotate and diminish in length, and they trace out a double-sided spiral path, known as the *Cornu spiral*.

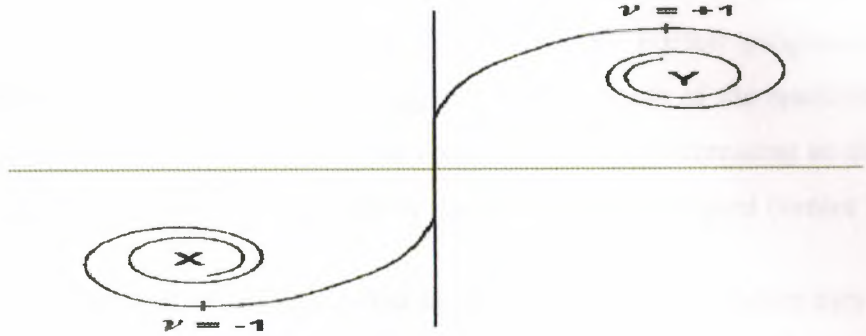


FIGURE 5.5 The Cornu Spiral

The Cornu spiral, shown in Fig. 5, provides the tool we need to visualize what happens when radio waves encounter an obstacle. In free space, at every point on a new wavefront, all contributions from the wavelets on the preceding wavefront are present and unattenuated, so the resultant vector corresponds to the complete spiral (i.e., the endpoints of the vector are X and Y). Now, consider again the situation shown in Fig. 1, and for each location on the wavefront B-B', visualize the makeup of the Cornu spiral (note that the top of the obstacle is assumed to be sufficiently narrow that no significant reflections can occur from it). At position 0, level with the top of the obstacle, we will have only contributions from the positive half of the preceding wavefront at A-A', since all of the others are blocked by the obstacle. Therefore, the received components form only the upper half of the spiral, and the resultant vector is exactly half the length of the free space case, corresponding to a 6 dB reduction in amplitude. As we go lower on the line B-B', we start to get blockage of components from the positive side of the A-A' wavefront, removing more and more of the vectors as we go, and leaving only the tight upper spiral.

The resulting amplitude diminishes monotonically towards zero as we move down the new wavefront, but there *is* still signal present at all points behind the obstacle, as shown in the graph in Fig. 2. How about the points along line B-B' *above* the obstacle, where the graph shows those mysterious ripples? Again, look at the Cornu spiral: as we move up the line, we begin to add contributions from the negative side of the A-A' wavefront (vectors -1, -2, etc.). Note what happens to the resultant vector - as we make the first turn around the bottom of the spiral, it reaches its maximum length, corresponding to the highest peak in the graph of Fig. 2. As we continue to move up B-B' and add more components, we swing around the spiral and reach the minimum length for the resultant vector (minimum distance from point Y). Further progression up B-B' results in further motion around the spiral, and the amplitude of the resultant oscillates back and forth, with the amplitude of the oscillation steadily decreasing as the resultant converges on the free space value, given by the complete Cornu spiral (vector X-Y).

So, in a nutshell, to visualize what happens to radio waves when they encounter an obstacle, we have to develop a picture of the wavefront after the obstacle as a function of the wavefront just before it (as opposed to simply tracing rays from the distant source). Now we're in a position to talk about Fresnel zones. A Fresnel zone is a simpler concept once you have some understanding of diffraction: it is the volume of space enclosed by an ellipsoid which has the two antennas at the ends of a radio link at its foci. The two-dimensional representation of a Fresnel zone is shown in Fig. 6. The surface of the ellipsoid is defined by the path ACB, which exceeds the length of the direct path AB by some fixed amount. This amount is $n\lambda/2$, where n is a positive integer. For the first Fresnel zone, n = 1 and the path length differs by $\lambda/2$ (i.e., a 180 phase reversal with respect to the direct path). For most practical purposes, only the first Fresnel zone need be considered. A radio path has *first Fresnel zone clearance* if, as shown in Fig. 6, no objects capable of causing significant diffraction penetrate the corresponding ellipsoid. What does this mean in terms of path loss? Recall how we constructed the wavefront behind an object by vector addition of the wavelets comprising the wavefront in front of the object, and apply this to the case where we have exactly first Fresnel zone clearance. We wish to find the strength of the direct path signal after it passes the object. Assuming there is only one such object near the Fresnel zone, we can look at the resultant wavefront at the destination point B. In terms of the Cornu spiral, the upper half of the spiral is intact, but part of the lower half is absent, due to blockage by the object. Since we have exactly first Fresnel clearance, the final vector which we add to the bottom of the spiral is 180 degrees out of phase with the direct-path vector - i.e., it is pointing downwards. This means that we have passed the bottom of the spiral and are on the way back up, and the resultant vector is near the free space magnitude (a line between X and Y in Fig. 5). In fact, it is sufficient to have 60% of the first Fresnel clearance, since this will still give a resultant which is very close to the free space value.

FIGURE 5.6 Fresnel Zone for A Radio Link

In order to quantify diffraction losses, they are usually expressed in terms of a dimensionless parameter , given by:

$$v = 2\sqrt{\frac{\Delta d}{\lambda}} \qquad (8)$$

where Δd is the difference in lengths of the straight-line path between the endpoints of the link and the path which just touches the tip of the diffracting object (see Fig. 7, where $\Delta d = d_1 + d_2 - d$). By convention, $v$is positive when the direct path is blocked (i.e., the obstacle has positive height), and negative when the direct path has some clearance ("negative height"). When the direct path just grazes the object, $v= 0$. This is the parameter shown in Figures 1 and 2. Since in this section we are considering LOS paths, this corresponds to specifying that $v$is negative (or zero). For first Fresnel zone clearance, we have $\Delta d = \lambda/2$, so from equation (8), $v= -1.4$. From Fig. 2, we can see that this is more clearance than necessary - in fact, we get slightly higher signal level (and path loss less than the free space value) if we reduce the clearance to $v= -1$, which corresponds to $\Delta d = \lambda/4$. The $v= -1$ point is also shown on the Cornu spiral in Fig. 5. Since $\Delta d= \lambda/4$, the last vector added to the summation is rotated 90 from the direct-path vector, which brings us to the lowest point on the spiral.

The resultant vector then runs from this point to the upper end of the spiral at point Y. It's easy to see that this vector is a bit longer than the distance from X to Y, so we have a slight gain (about 1.2 dB) over the free space case. We can also see how we can back off to 60% of first Fresnel zone clearance (ν = -0.85) without suffering significant loss.

But how do we calculate whether we have the required clearance? The geometry for Fresnel zone calculations is shown in Fig. 7. Keep in mind that this is only a two-dimensional representation, but Fresnel zones are three-dimensional. The same considerations apply when the objects limiting path clearance are to the side or even above the radio path. Since we are considering LOS paths in this section, we are dealing only with the "negative height" case, shown in the lower part of the figure. We will look at the case where h is positive later, when we consider non-LOS paths.

For first Fresnel zone clearance, the distance h from the nearest point of the obstacle to the direct path must be at least

$$h = 2\sqrt{\frac{\lambda\, d_1 d_2}{d_1 + d_2}} \quad (9)$$

where d_1 and d_2 are the distances from the tip of the obstacle to the two ends of the radio circuit. This formula is an approximation which is not valid very close to the endpoints of the circuit. For convenience, the clearance can be expressed in terms of frequency:

$$h = 17.3\sqrt{\frac{d_1 d_2}{f(d_1 + d_2)}} \quad (10a)$$

where f is the frequency in GHz, d_1 and d_2 are in km, and h is in meters. Or:

$$h = 72.1\sqrt{\frac{d_1 d_2}{f(d_1 + d_2)}} \quad (10b)$$

where f is in GHz, d_1 and d_2 in statute miles, and h is in feet.

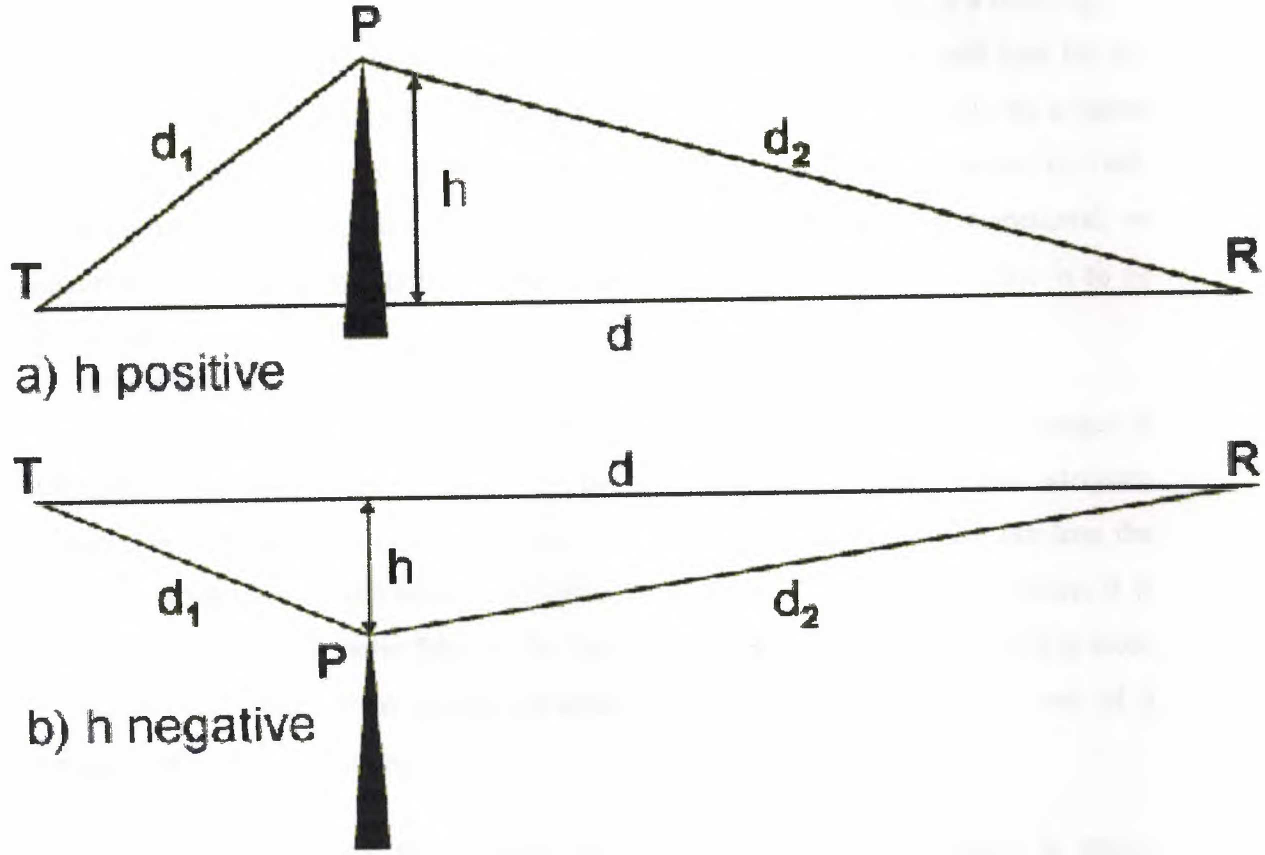


FIGURE 5.7 Fresnel Zone Geometry

Example 2. We have a 10 km LOS path over which we wish to establish a link in the 915 MHz band. The path profile indicates that the high point on the path is 3 km from one end, and the direct path clears it by about 18 meters (60 ft.) - do we have adequate Fresnel zone clearance? From equation (10a), with d_1 = 3 km, d_2 = 7 km, and f = 0.915 GHz, we have h = 26.2 m for first Fresnel zone clearance (strictly speaking, h = -26.2 m). A clearance of 18 m is about 70% of this, so it is sufficient to allow negligible diffraction loss.

Fresnel zone clearance may not seem all that important - after all, we said previously that for the zero clearance (grazing) case, we have 6 dB of additional path loss. If necessary, this could be overcome with, for example, an additional 3 dB of antenna gain at each end of the circuit. Now it's time to confess that the situation depicted in Figures 1 and 2 is a special case, known as "knife edge" diffraction. Basically, this means that the top of the obstacle is small in terms of wavelengths. This is *sometimes* a reasonable approximation of an object in the real world, but more often than not, the obstacle will be rounded (such as a hilltop) or have a large flat surface (like the top of a building), or otherwise depart from the knife edge assumption. In such cases, the path loss for the grazing case can be considerably more than 6 dB - in fact, 20 dB would be a better estimate in many cases. So, Fresnel zone clearance can be pretty important on real-world paths. And, again, keep in mind that the Fresnel zone is three-dimensional, so clearance must also be maintained from the sides of buildings, etc. if path loss is to be minimized.

Another point to consider is the effect on Fresnel zone clearance of changes in atmospheric refraction, as discussed in the last section. We may have adequate clearance on a longer path under normal conditions (i.e., 4/3 earth radius), but lose the clearance when unusual refraction conditions prevail. On longer paths, therefore, it is common in commercial radio links to do the Fresnel zone analysis on something close to "worst case" rather than typical refraction conditions, but this may be less of a concern in amateur applications.

Most of the material in this section was based on Ref. [2], which is highly recommended for further reading.

5.3.3 Ground Reflections

An LOS path may have adequate Fresnel zone clearance, and yet still have a path loss which differs significantly from free space under normal refraction conditions. If this is the case, the cause is probably multipath propagation resulting from reflections (multipath also poses particular problems for digital transmission systems - we'll look at this a bit later, but here we are only considering path loss).

One common source of reflections is the ground. It tends to be more of a factor on paths in rural areas; in urban settings, the ground reflection path will often be blocked by the clutter of buildings, trees, etc. In paths over relatively smooth ground or bodies of water, however, ground reflections can be a major determinant of path loss. For any radio link, it is worthwhile to look at the path profile and see if the ground reflection has the potential to be significant. It should also be kept in mind that the reflection point is not at the midpoint of the path unless the antennas are at the same height and the ground is not sloped in the reflection region - just the remember the old maxim from optics that the angle of incidence equals the angle of reflection.

Ground reflections can be good news or bad news, but are more often the latter. In a radio path consisting of a direct path plus a ground-reflected path, the path loss depends on the relative amplitude and phase relationship of the signals propagated by the two paths. In extreme cases, where the ground-reflected path has Fresnel clearance and suffers little loss from the reflection itself (or attenuation from trees, etc.), then its amplitude may approach that of the direct path. Then, depending on the relative phase shift of the two paths, we may have an enhancement of up to 6 dB over the direct path alone, or cancellation resulting in additional path loss of 20 dB or more. If you are acquainted with Mr.

Murphy, you know which to expect! The difference in path lengths can be estimated from the path profile, and then translated into wavelengths to give the phase relationship. Then we have to account for the reflection itself, and this is where things get interesting. The amplitude and phase of the reflected wave depend on a number of variables, including conductivity and permittivity of the reflecting surface, frequency, angle of incidence, and polarization.

It is difficult to summarize the effects of all of the variables which affect ground reflections, but a typical case is shown in Fig. 8 [2]. This particular figure is for typical ground conditions at 100 MHz, but the same behavior is seen over a wide range of ground constants and frequencies. Notice that there is a large difference in reflection amplitudes between horizontal and vertical polarization (denoted on the curves with "h" and "v", respectively), and that vertical polarization in general gives rise to a much smaller reflected wave. However, the difference is large only for angles of incidence greater than a few degrees (note that, unlike in optics, in radio transmission the angle of incidence is normally measured with respect to a tangent to the reflecting surface rather than a normal to it); in practice, these angles will only occur on very short paths, or paths with extraordinarily high antennas. For typical paths, the angle of incidence tends to be of the order of one degree or less - for example, for a 10 km path over smooth earth with 10 m antenna heights, the angle of incidence of the ground reflection would only be about 0.11 degrees. In such a case, both polarizations will give reflection amplitudes near unity (i.e., no reflection loss). Perhaps more surprisingly, there will also be a phase reversal in both cases. Horizontally-polarized waves always undergo a phase reversal upon reflection, but for vertically-polarized waves, the phase change is a function of the angle of incidence and the ground characteristics.

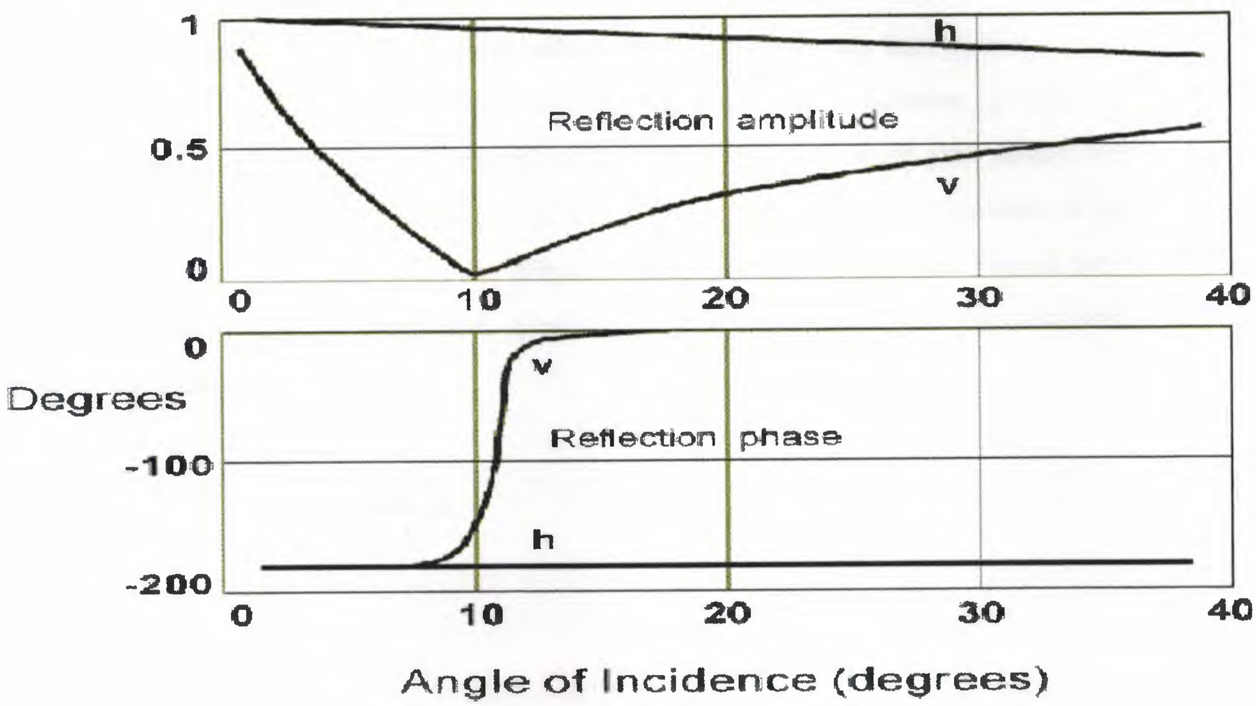


FIGURE 5.8 Typical Ground Reflection Parameters

The upshot of all this is that for most paths in which the ground reflection is significant (and no other reflections are present), there will be very little difference in performance between horizontal and vertical polarization. For very short paths, horizontal polarization will generally give rise to a stronger reflection. If it turns out that this causes cancellation rather than enhancement, switching to vertical polarization may provide a solution. In other words, for shorter paths, it is usually worthwhile to try both polarizations to see which works better (of course, other factors such as mounting constraints and rejection of other sources of multipath and interference also enter into the choice of polarization).

As stated above, for either polarization, as the path gets longer we approach the case where the ground reflection produces a phase reversal and very little attenuation. At the same time, the direct and reflected paths are becoming more nearly equal. The path loss ripples up and down as we increase the distance, until we reach the point where the path lengths differ by just one-half wavelength. Combined with the 180° phase shift caused by the ground reflection, this brings the direct and reflected signals into phase, resulting in an enhancement over the free space path loss (theoretically 6 dB, but this will seldom be realized in practice). Thereafter, it's all downhill as the distance is further increased, since phase difference between the two paths approaches in the limit the 180° phase shift of the ground reflection. It can be shown that, in this region, the received power follows an inverse fourth-power law as a function of distance instead of the usual square law (i.e., 12 dB more attenuation when you double the distance, instead of 6 dB). The distance at which the path loss starts to increase at the fourth-power rate is reached when the ellipsoid corresponding to the first Fresnel zone just touches the ground. A reasonably good estimate of this distance can be calculated from the equation

$$d = \frac{4h_1h_2}{\lambda} \tag{11}$$

where h_1 and h_2 are the antenna heights above the ground reflection point. For example, for antenna heights of 10 m, at 915 MHz ($\lambda = 33$ cm) we will be into the fourth-law loss region for links longer than about 1.2 km.

So, for longer-range paths, ground reflections are always bad news. Serious problems with ground reflections are most commonly encountered with radio links across bodies of water. Spread spectrum techniques and diversity antenna arrangements usually can't overcome the problems - the solution lies in siting the antennas (e.g., away from the shore of the body of water) such that the reflected path is cut off by natural obstacles, while the direct path is unimpaired. In other cases, it may be possible to adjust the antenna locations so as to move the reflection point to a rough area of land which scatters the signal rather than creating a strong specular reflection.

5.3.4 Other Sources of Reflections

Much of what has been said about ground reflections applies to reflections from other objects as well. The "ground reflection" on a particular path may be from a building rooftop rather than the ground itself, but the effect is much the same. On long links, reflections from objects near the line of the direct path will almost always cause increased path loss - in essence, you have a permanent "flat fade" over a very wide bandwidth. Reflections from objects which are well off to the side of the direct path are a different story, however. This is a frequent occurrence in urban areas, where the sides of buildings can cause strong reflections. In such cases, the angle of incidence may be much larger than zero, unlike the ground reflection case.

This means that horizontal and vertical polarization may behave quite differently - as we saw in Fig. 8, vertically polarized signals tend to produce lower-amplitude reflections than horizontally polarized signals when the angle of incidence exceeds a few degrees. When the reflecting surface is vertical, like the side of a building, a signal which is transmitted with horizontal polarization effectively has vertical polarization as far as the reflection is concerned. Therefore, horizontal polarization will generally result in weaker reflections and less multipath than vertical polarization in these cases.

5.3.5 Effects of Rain, Snow and Fog

The loss of LOS paths may sometimes be affected by weather conditions (other than the refraction effects which have already been mentioned). Rain and fog (clouds) become a significant source of attenuation only when we get well into the microwave region. Attenuation from fog only becomes noticeable (i.e., attenuation of the order of 1 dB or more) above about 30 GHz. Snow is in this category as well. Rain attenuation becomes significant at around 10 GHz, where a heavy rainfall may cause additional path loss of the order of 1 dB/km.

5.4 Path Loss on Non-Line of Sight Paths

We have spent quite a bit of time looking at LOS paths, and described the mechanisms which often cause them to have path loss which differs from the "free space" assumption. We've seen that the path loss isn't always easy to predict. When we have a path which is not LOS, it becomes even more difficult to predict how well signals will propagate over it. Unfortunately, non-LOS situations are sometimes unavoidable, particularly in urban areas. The following sections deal with some of the major factors which must be considered.

5.4.1 Diffraction Losses

In some special cases, such as diffraction over a single obstacle which can be modeled as a knife edge, the loss of a non-LOS path can be predicted fairly readily. In fact, this is the same situation that we saw in Figures 1 and 2, with the diffraction parameter $\nu > 0$. This parameter, from equation (8), is

$$\nu = 2\sqrt{\frac{\Delta d}{\lambda}} \qquad (11)$$

To get Δd, measure the straight-line distance between the endpoints of the link. Then measure the length of the actual path, which includes the two endpoints and the tip of the knife edge, and take the difference between the two. The geometry is shown in Fig. 7(a), the "positive h" case. A good approximation to the knife-edge diffraction loss in dB can then be calculated from

$$L(\nu) = 6.9 + 20\log\left[\sqrt{\nu^2+1} + \nu\right] \qquad (12)$$

Example 3. We want to run a 915 MHz link between two points which are a straight-line distance of 25 km apart. However, 5 km from one end of the link, there is a ridge which is 100 meters higher than the two endpoints. Assuming that the ridge can be modeled as a knife edge, and that the paths from the endpoints to the top of ridge are LOS with adequate Fresnel zone clearance, what is the expected path loss? From simple geometry, we find that length of the path over the ridge is 25,001.25 meters, so that d = 1.25 m. Since $\lambda = 0.33$ m, the parameter ν, from (8), is 3.89. Substituting this into (12), we find that the expected diffraction loss is 24.9 dB. The free space path loss for a

25 km path at 915 MHz is, from equation (6a), 119.6 dB, so the total predicted path loss for this path is 144.5 dB. This is too lossy a path for many WLAN devices. For example, suppose we are using WaveLAN cards with 13 dBi gain antennas, which (disregarding feedline losses) brings them up to the maximum allowable EIRP of +36 dBm. This will produce, at the antenna terminals at the other end of the link, a received power of (36 - 144.5 + 13) = -95.5 dBm. This falls well short of the -78 dBm requirement of the WaveLAN cards. On the other hand, a lower-speed system may be quite usable over this path. For instance, the FreeWave 115 Kbps modems require only about -108 dBm for reliable operation, which is a comfortable margin below our predicted signal levels.

To see the effect of operating frequency on diffraction losses, we can repeat the calculation, this time using 144 MHz, and find the predicted diffraction loss to be 17.5 dB, or 7.4 dB less than at 915 MHz. At 2.4 GHz, the predicted loss is 29.0 dB, an increase of 4.1 dB over the 915 MHz case (these differences are for the diffraction losses only, not the only total path loss).

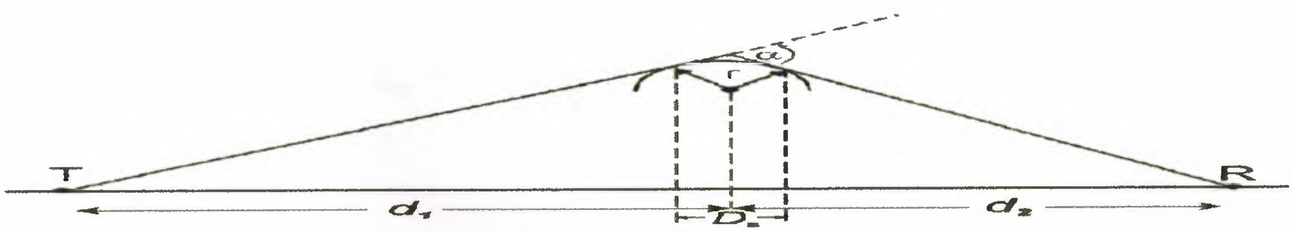


FIGURE 5.9 Diffraction By A Rounded Obstacle

Unfortunately, the paths which digital experimenters are faced with are seldom this simple. They will frequently involve diffraction over multiple rooftops or other obstacles, many of which don't resemble knife edges. The path losses will generally be substantially greater in these cases than predicted by the single knife edge model. The paths will also often pass through objects such as trees and wood-frame buildings which are semi-transparent at radio frequencies. Many models have been developed to try and predict path losses in these more complex cases. The most successful are those which deal with restricted scenarios rather than trying to cover all of the possibilities. One common scenario is diffraction over a single obstacle which is too rounded to be considered a knife edge. There are different ways of treating this problem; the one described here is from Ref. [3]. The top of the object is modeled as a cylinder of radius r, as shown in Fig. 9. To calculate the loss, you need to plot the profile of the actual object, and then draw straight lines from the link endpoints such that they just graze the highest part of the object as seen from their individual perspectives. Then the parameters D_s, d_1, d_2 and are estimated, and an estimate of the radius r can then be calculated from

$$r = \frac{2 D_s d_1 d_2}{\alpha \left(d_1^2 + d_2^2\right)} \quad (13)$$

Note that the angle is measured in radians. The procedure then is to calculate the knife edge diffraction loss for this path as outlined above, and then add to it an excess loss factor L_{ex}, calculated from

$$L_{ex} = 11.7 \alpha \sqrt{\frac{\pi r}{\lambda}} \ dB \quad (14)$$

There is also a correction factor for roughness: if the object is, for example, a hill which is tree-covered rather than smooth at the top, the excess diffraction loss is said to be about 65% of that predicted in (14). In general, smoother objects produce greater diffraction losses.

Example 4. We revisit the scenario in Example 3, but let's suppose that we've now decided that the ridge blocking our path doesn't cut it as a knife edge (ouch!). From a plot of the profile, we estimate that D_s = 10 meters. As before, d_1 = 20 km, d_2 = 5 km and the height of the ridge is 100 meters. Dusting off our high school trigonometry, we can work out that α= 1.43, or 0.025 radians. Now, plugging these numbers into (13), we get r = 188 meters. Then, with λ= 0.33 m, we can calculate the excess loss from (14):

$$L_{ex} = 11.7 \times 0.025 \times \sqrt{\frac{\pi \times 188}{0.33}} = 12.4 \ dB$$

So, summed with the knife edge loss calculated previously, we have an estimated total diffraction loss of 37.3 dB (assuming the ridge is "smooth" rather than "rough"). This is a lot, but you can easily imagine scenarios where the losses are much greater: just look at the direct dependence on the angle in (14) and picture from Fig. 9 what happens when the obstacle is closer to one of the link endpoints. Amateurs doing weak signal work are accustomed to dealing with large path losses in non-LOS propagation, but such losses are usually intolerable in high-speed digital links.

5.4.2 Attenuation from Trees and Forests

Trees can be a significant source of path loss, and there are a number of variables involved, such as the specific type of tree, whether it is wet or dry, and in the case of deciduous trees, whether the leaves are present or not. Isolated trees are not usually a major problem, but a dense forest is another story. The attenuation depends on the distance the signal must penetrate through the forest, and it increases with frequency. According to a CCIR report [10], the attenuation is of the order of 0.05 dB/m at 200 MHz, 0.1 dB/m at 500 MHz, 0.2 dB/m at 1 GHz, 0.3 dB/m at 2 GHz and 0.4 dB/m at 3 GHz. At lower frequencies, the attenuation is somewhat lower for horizontal polarization than for vertical, but the difference disappears above about 1 GHz. This adds up to a *lot* of excess path loss if your signal must penetrate several hundred meters of forest! Fortunately, there is also significant propagation by diffraction over the treetops, especially if you can get your antennas up near treetop level or keep them a good distance from the edge of the forest, so all is not lost if you live near a forest.

5.4.3 General Non-LOS Propagation Models

There are many more general models and empirical techniques for predicting non-LOS path losses, but the details are beyond the scope of this paper. Most of them are aimed at prediction of the paths between elevated base stations and mobile or portable stations near ground level, and they typically have restrictions on the frequency range and distances for which they are valid; thus they may be of limited usefulness in the planning of amateur high-speed digital links. Nevertheless, they are well worth studying to gain further insight into the nature of non-LOS propagation. The details are available in many texts - Ref. [3] has a particularly good treatment. One crude, but useful, approximation will be mentioned here: the loss on many non-LOS paths in urban areas can be modeled quite well by a fourth-power distance law. In other words, we substitute d^4 for d^2 in equation (5). In equation (6), we can substitute 40log(d) for the 20log(d) term, which would correspond to the assumption of square-law distance loss for distances up to 1 km (or 1 mile, for the non-metric version of the equation), and fourth-law loss thereafter. This is probably an overly optimistic assumption for heavily built-up areas, but is at least a useful starting point.

The propagation losses on non-LOS paths can be discouragingly high, particularly in urban areas. Antenna height becomes a critical factor, and getting your antennas up above rooftop heights will often spell the difference between success and failure. Due to the great variability of propagation in cluttered urban environments, accurate path loss predictions can be difficult. If a preliminary analysis of the path indicates that you are at least in the ballpark (say within 10 or 15 dB) of having a usable link, then it will generally be worthwhile to give it a try and hope to be pleasantly surprised (but be prepared to be disappointed!).

5.5 Software Tools for Propagation Prediction

Although there is no substitute for experience and acquiring a "feel" for radio propagation, computer programs can make the job of predicting radio link performance a lot easier. They are particularly handy for exploring "what if" scenarios with different paths, antenna heights, etc. Unfortunately, they also tend to cost money! If you're lucky, you may have access to one of the sophisticated prediction programs which includes the most complex propagation models, terrain databases, etc. If not, you can still find some free software utilities that will make it easier to do some of the calculations discussed above, such as knife edge diffraction losses. One very useful freeware program which was developed specifically for short-range VHF/UHF applications is **RFProp**, by Colin Seymour,G4NNA.CheckColin'Webpageathtp://www.users.dircon.co.uk/~netking/frees w.htm for more information and downloading instructions. This is a Windows (3.1, 95 or NT) program which can calculate path loss in free space and simple diffraction scenarios. In addition to calculating knife edge diffraction loss, it provides some correction factors for estimating the loss caused by more rounded objects, such as hills. It also allows changing the distance loss exponent from square-law to fourth-law (or anything else, for that matter) to simulate long paths with ground reflections or obstructed urban paths. There is also some provision for estimating the loss caused when the signals must penetrate buildings. The program has a graphical user interface in which the major path parameters can be entered and the result (in terms of receiver SNR margin) seen immediately. There is also a tabular output which lists the detailed results along with all of the assumed parameters.

5.6 Special Considerations for Digital Systems

We have previously looked at the effect of multipath on path loss. When reflections occur from objects which are very close to the direct path, then paths have very similar lengths and nearly the same time delay. Depending on the relative phase shifts of the paths, the signals traversing them at a given frequency can add constructively to provide a gain with respect to a single path, or destructively to provide a loss. On longer paths in particular, the effect is usually a loss. Since the path lengths are nearly equal, the loss occurs over a wide frequency range, producing a "flat" fade.

In many cases, however, reflections from objects well away from the direct path can give rise to significant multipath. The most common reflectors are buildings and other manmade structures, but many natural features can also be good reflectors. In such cases, the propagation delays of the paths from one end of the link to the other can differ considerably. The extent of this time spreading of the signal is commonly measured by a parameter known as the *delay spread* of the path. One consequence of having a larger delay spread is that the reinforcement and cancellation effects will now vary more rapidly with frequency. For example, suppose we have two paths with equal attenuation and which differ in length by 300 meters, corresponding to a delay difference of 1 μsec. In the frequency domain, this link will have deep nulls at intervals of 1 MHz, with maxima in between.

With a narrowband system, you may be lucky and be operating at a frequency near a maximum, or you may be unlucky and be near a null, in which case you lose most of your signal (techniques such as space diversity reception may help, though). The path loss in this case is highly frequency-dependent. On the other hand, a wideband signal which is, say, several MHz wide, would be subject to only partial cancellation or *selective* fading. Depending on the nature of the signal and how information is encoded into it, it may be quite tolerant of having part of its energy notched out by the multipath channel. Tolerance of multipath-induced signal cancellation is one of the major benefits of spread spectrum (SS) transmission techniques.

Longer multipath delay spreads have another consequence where digital signals are concerned, however: overlap of received data symbols with adjacent symbols, known as *intersymbol interference* or ISI. Suppose we try to transmit a 1 Mbps data stream over the two-path multipath channel mentioned above. Assuming a modulation scheme with 1 sec symbol length is used, then the signals arriving over the two paths will be offset by exactly one symbol period. Each received symbol arriving over the shorter path will be overlaid by a copy of the previous symbol from the longer path, making it impossible to decode with standard demodulation techniques. This problem can be solved by using an adaptive equalizer in the receiver, but this level of sophistication is not commonly found in amateur or WLAN modems (but it will certainly become more common as speeds continue to increase). Another way to attack this problem is to increase the symbol length while maintaining a high bit rate by using a multicarrier modulation scheme such as OFDM (Orthogonal Frequency Division Multiplex), but again, such techniques are seldom found in the wireless modem equipment available to hobbyists.

For unequalized multipath channels, the delay spread must be much less than the symbol length, or the link performance will suffer greatly. The effect of multipath-induced ISI is to establish an *irreducible error rate* - beyond a certain point, increasing transmitter power will cause no improvement in BER, since the BER vs E_b/N_0 curve has gone flat. A common rule of thumb prescribes that the multipath delay spread should be no more than about 10% of the symbol length. This will generally keep the irreducible error rate down to the order of 10^{-3} or less. Thus, in our two-path example above, a system running at 100K symbols/s or less may work satisfactorily. The actual raw BER requirements for a particular system will of course depend on the error-control coding technique used.

Although it is commonly believed that SS modulation schemes solve the multipath ISI problem, this is not really the case. As stated above, SS can convert a flat-faded channel into one which has selective fading, which is a good thing. In the case of Frequency Hopping (FHSS), it means that signal cancellation due to multipath will occur only a fraction of the time (i.e., only on some of the channels we hop to), and we can recover the data by means of Forward Error Correction (or by error detection and retransmission). In the case of Direct Sequence (DSSS), only a fraction of the transmitted spectrum is notched out by the multipath cancellation. This causes some degradation of the BER, but again error control coding can be used to compensate for this. In both cases, SS modulation has given us a form of frequency diversity. For DSSS, the large continuous spread bandwidth allows us to resolve many of the multipath components (those separated by delays of approximately the reciprocal of the spread bandwidth, or more). These appear as separate peaks in the DSSS receiver correlator output. A diversity receiver using the RAKE principle can take advantage of some of the multipath signal power by combining it constructively before making the bit decisions. More commonly, however, only the largest correlation peak is used, and all of the other multipath energy represents wideband interference. Regardless of whether a diversity receiver structure is used, however, ISI (and hence BER degradation) will *still occur* when the multipath delay spread approaches the same order of magnitude as the information symbol length. An excellent discussion of these concepts can be found in chapter 9 of Ref. [11].

As an illustration, consider again the WaveLAN product, which is a DSSS system using DQPSK modulation, a spread bandwidth of 11 MHz, and a symbol length of 1 μsec. Tests of WaveLAN using a channel simulator [12] have shown that its performance degrades when the delay spread exceeds 84 nsec (0.084 μsec), which is only about 10% of the symbol length.

Delay spreads of several microseconds are not uncommon, especially in urban areas. Mountainous areas can produce much longer delay spreads, sometimes tens of microseconds. This spells big trouble for doing high-speed data transmission in these areas. The best way to mitigate multipath in these situations is to use highly directional antennas, preferably at both ends of the link. The higher the data rate, the more critical it becomes to use high-gain antennas. This is one advantage to going higher in frequency. The delay spread for a given link will usually not exhibit much frequency dependence - for example, there will be similar amounts of multipath whether you operate at 450 MHz or 2.4 GHz, *if* you use the same antenna gain and type. However, you can get more directivity at the higher frequencies, which often will result in significantly reduced multipath delay spread and hence lower BER. It may seem strange that high-speed WLAN products are often supplied with omnidirectional antennas which do nothing to combat multipath, but this is because the antennas are intended for indoor use. The attenuation provided by the building structure will usually cause a drastic reduction in the amplitude of reflections from outside the building, as well as from distant areas inside the building. Delay spreads therefore tend to be much smaller inside buildings - typically of the order of 0.1 μsec or less. However, as WLAN products with data rates of 10 Mbps and beyond are now appearing, even delay spreads of this magnitude are problematic and must be dealt with by such measures as equalizers, high-level modulation schemes and sectorized antennas.

CHAPTER 6

INDOOR RADOI PROPAGATION

6.1 In door RF Propagation

RF propagation obstacles can be termed hard partitions if they are part of the physical / structural components of a building. On the other hand, obstacles formed by the office furniture and fixed or movable / portable structures that do not extend to a buildings ceiling are considered soft partitions. Radio signals effectively penetrate both kinds of obstacles or partitions in ways that are very hard to predict.

Remember that in free space, an additional signal loss of 20 dB is incurred for each 10 to 1 increase in radio range. Thus, an obstacle with a measured loss of 20 dB or more from its materials is a significant loss! The equivalent of RF transparent is probably in the range of 3 to 6 dB loss from any obstacle's material properties.

We cannot do anything about the buildings, building materials or structures this system will be used in, however, we must still explore the realm of overall macroscopic signal propagation in a typical building. Electronic engineers (radio engineers, in particular) would like to be able to predict the signal levels and range of signal losses present in a building. To enable this prediction a number of studies and measurements have been made which grossly characterize in building signal propagation. Figure 2 (ref. 2), below, shows scatter plots of radio path loss as a function of distance in a typical office building for propagation through one through four floors. Figure 6,1 below, shows measurements made at another "typical" building. Observe that both sets of data were taken at 914 MHz, not 2400 MHz and that data is shown for propagation on the same floor as well as between floors.

We can extrapolate this data for use at 2400 MHz with a fair amount of certainty, if we add a few dB (perhaps 5 to 6 dB) to account for the higher frequency we will use to each graph point.

Interpretation of this data provides a level of understanding of the potential problem at hand. Figure 6.2 shows losses ranging from about 50 dB to over 80 dB for a transmitter-receiver separation of only 10 meters. Figure 3 shows even higher losses, extrapolating to our frequency range gives us over 50 dB to over 90 dB attenuation in a 10 meter separation!

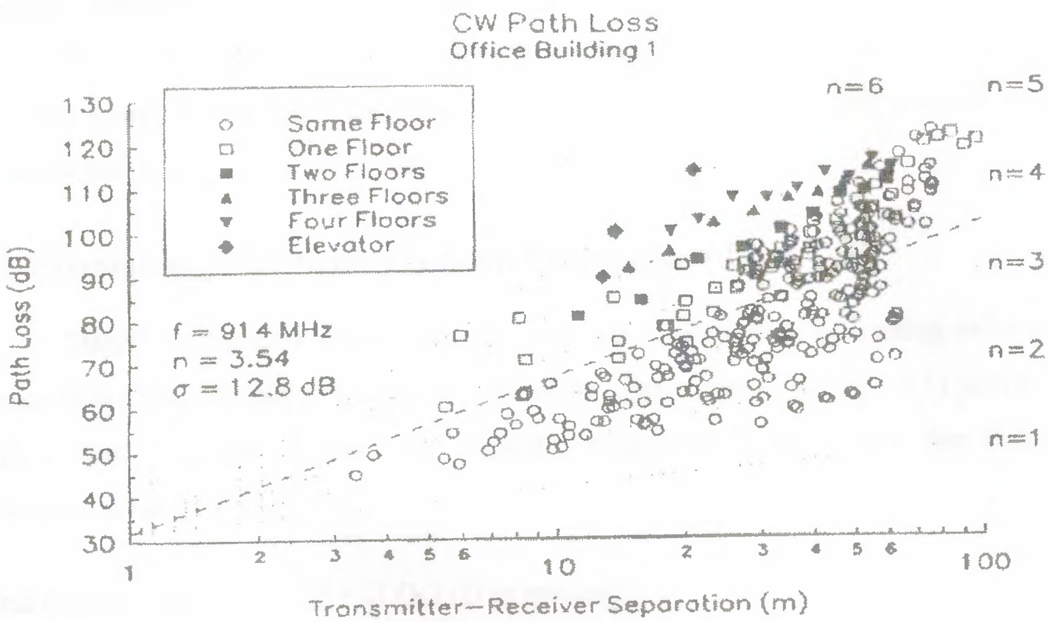


Figure 6.1 Path Loss Scatter Plot in a Typical Building.

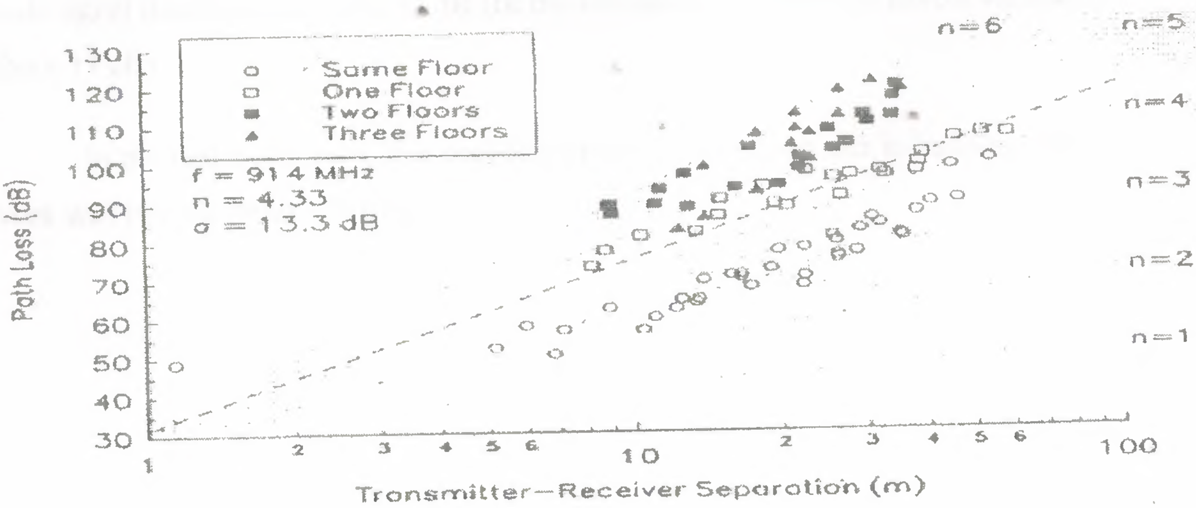


Figure 6.2 Path Loss Scatter Plot in Another Typical Building.

Given that the entire loss budget for the typical indoor wireless link is in the neighborhood of 120 dB, most of our losses seem to be expected in the very first 10 meters! However, this interpretation of the data presented in Figures 2 and 3 takes the entire realm of multi-story building propagation into account. This is perhaps not fair in the current context. If we confine ourselves to same floor only propagation, then losses at 10 meters can be expected to be about 60 dB. However, going out to a 50 meter range between transmitter and receiver causes losses as high as 110 dB -- almost all of our loss budget will disappear by 50 meters! So, can we begin to characterize losses between rooms and through the various radio obstacles and hard / soft partitions within a typical building?

6.2 Estimating / Predicting Indoor Propagation Loss

Based on the data above, as a first cut approximation to estimating indoor path losses, if we assume that propagation follows an approximate 1/(range^3.5) power rule, rather than 1/(range^2), we can predict propagation losses with the following relationship (at 2.4 GHz):

Path Loss (in dB) = 40 + 35 * [LOG (D in meters)]

Thus a 10 meter path will give a loss of about 75 dB and a 100 meter path gives a path loss of about 110 dB. If the data above are fairly accurate, we can expect a large-scale signal flucuation of about 13 dB (or the estimated path loss will have a variance of about 13 dB).

In the real world then, it is probably optimistic to expect our in-building links to work well beyond about 100 meters!

CONCLUSIONS

Radio propagation is a vast topic, and we've only scratched the surface here. We haven't considered, for example, the interesting area of data transmission involving mobile stations - maybe, this project has provided some insight into the problems and solutions associated with setting up digital links in the VHF to microwave spectrum. To sum up, here are a few guidelines and principles:

- Always strive for LOS conditions. Even with LOS, you must pay attention to details regarding variability of refractivity, Fresnel zone clearance and avoiding reflections from the ground and other surfaces. Non-LOS paths will often lead to disappointment unless they are very short, especially with the high-speed unlicenced WLAN devices. Their low ERP limits and high receive signal power requirements (due to large noise bandwidths, high noise figures and sometimes, significant modem implementation losses) leave little margin for higher-than-LOS path losses. Hams are not encumbered by the low ERP limits, but it can be very expensive to overcome excessive path losses with higher transmitter powers.

- Use as much antenna gain as is practical. It is always worthwhile to try both polarizations, but horizontal polarization will often be superior to vertical. It will generally provide less multipath in urban areas, and may provide lower path loss in some non-LOS situations (e.g., attenuation from trees at VHF and lower UHF). Also, interfering signals from pagers and the like tend to be vertically polarized, so using the opposite polarization can often provide some protection from them.

- There are advantages to going higher in frequency, into the microwave bands, due to the higher antenna gains which can be achieved. The tighter focusing of energy which can be achieved may result in lower overall path loss on LOS paths (providing that you can keep the feedline losses under control), and less multipath. Higher frequencies also have smaller Fresnel zones, and thus require less clearance over obstacles to avoid diffraction losses. And, of course, the higher bands have more bandwidth available for high-speed data, and less probability of interference. However, the advantage may be lost in non-LOS situations, since diffraction losses, and attenuation from natural objects such as trees, increase with frequency.

- This report has tried to make some sense out of the mysteries of radio propagation within buildings. We have presented measured data and come up with an approximate formula for the average signal losses to be expected at 2.4 GHz in typical indoor environments,We have shown that a reasonable range of indoor radio propagation phenomenon can be handled by a practical system at distances out to perhaps 100 meters.
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Radio propagation is seldom 100% predictable, and one should never hesitate to experiment. It's very useful, though, to be equipped with enough knowledge to know what techniques to try, and when there is little probability of success. This paper was intended to help fill some gaps in that knowledge. Good luck with *your* radio links!

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