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Law Enforcement and Corrections Standards and Testing Program

Antenna System Guide

NIJ Guide 202–00

ABOUT THE LAW ENFORCEMENT AND CORRECTIONS STANDARDS AND TESTING PROGRAM

The Law Enforcement and Corrections Standards and Testing Program is sponsored by the Office of Science and Technology of the National Institute of Justice (NIJ), U.S. Department of Justice. The program responds to the mandate of the Justice System Improvement Act of 1979, which directed NIJ to encourage research and development to improve the criminal justice system and to disseminate the results to Federal, State, and local agencies.

The Law Enforcement and Corrections Standards and Testing Program is an applied research effort that determines the technological needs of justice system agencies, sets minimum performance standards for specific devices, tests commercially available equipment against those standards, and disseminates the standards and the test results to criminal justice agencies nationally and internationally.

The program operates through:

The *Law Enforcement and Corrections Technology Advisory Council* (LECTAC), consisting of nationally recognized criminal justice practitioners from Federal, State, and local agencies, which assesses technological needs and sets priorities for research programs and items to be evaluated and tested.

The *Office of Law Enforcement Standards* (OLES) at the National Institute of Standards and Technology, which develops voluntary national performance standards for compliance testing to ensure that individual items of equipment are suitable for use by criminal justice agencies. The standards are based upon laboratory testing and evaluation of representative samples of each item of equipment to determine the key attributes, develop test methods, and establish minimum performance requirements for each essential attribute. In addition to the highly technical standards, OLES also produces technical reports and user guidelines that explain in nontechnical terms the capabilities of available equipment.

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FOREWORD

The Office of Law Enforcement Standards (OLES) of the National Institute of Standards and Technology furnishes technical support to the National Institute of Justice program to strengthen law enforcement and criminal justice in the United States. OLES's function is to conduct research that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment.

OLES is: (1) subjecting existing equipment to laboratory testing and evaluation, and (2) conducting research leading to the development of several series of documents, including national standards, user guides, and technical reports.

This document covers research conducted by OLES under the sponsorship of the National Institute of Justice. Additional reports as well as other documents are being issued under the OLES program in the areas of protective clothing and equipment, communications systems, emergency equipment, investigative aids, security systems, vehicles, weapons, and analytical techniques and standard reference materials used by the forensic community.

Technical comments and suggestions concerning this document are invited from all interested parties. They may be addressed to the Director, Office of Law Enforcement Standards, National Institute of Standards and Technology, Gaithersburg, MD 20899–8102.

Dr. David G. Boyd, Director
Office of Science and Technology
National Institute of Justice

BACKGROUND

The Office of Law Enforcement Standards (OLES) was established by the National Institute of Justice (NIJ) to provide focus on two major objectives: (1) to find existing equipment which can be purchased today, and (2) to develop new law-enforcement equipment which can be made available as soon as possible. A part of OLES's mission is to become thoroughly familiar with existing equipment, to evaluate its performance by means of objective laboratory tests, to develop and improve these methods of test, to develop performance standards for selected equipment items, and to prepare guidelines for the selection and use of this equipment. All of these activities are directed toward providing law enforcement agencies with assistance in making good equipment selections and acquisitions in accordance with their own requirements.

As the OLES program has matured, there has been a gradual shift in the objectives of the OLES projects. The initial emphasis on the development of standards has decreased, and the emphasis on the development of guidelines has increased. For the significance of this shift in emphasis to be appreciated, the precise definitions of the words "standard" and "guideline" as used in this context must be clearly understood.

A "standard" for a particular item of equipment is understood to be a formal document, in a conventional format, that details the performance that the equipment is required to give and describes test methods by which its actual performance can be measured. These requirements are technical and are stated in terms directly related to the equipment's use. The basic purposes of a standard are (1) to be a reference in procurement documents created by purchasing officers who wish to specify equipment of the "standard" quality, and (2) to objectively identify equipment of acceptable performance.

Note that a standard is not intended to inform and guide the reader; that is the function of a "guideline." Guidelines are written in nontechnical language and are addressed to the potential user of the equipment. They include a general discussion of the equipment, its important performance attributes, the various models currently on the market, objective test data where available, and any other information that might help the reader make a rational selection among the various options or alternatives available.

Kathleen Higgins
National Institute of Standards and Technology
April 2001

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FIGURES

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COMMONLY USED SYMBOLS AND ABBREVIATIONS

A	ampere	H	henry	nm	nanometer
ac	alternating current	h	hour	No.	number
AM	amplitude modulation	hf	high frequency	o.d.	outside diameter
cd	candela	Hz	hertz	Ω	ohm
cm	centimeter	i.d.	inside diameter	p.	page
CP	chemically pure	in	inch	Pa	pascal
c/s	cycle per second	IR	infrared	pe	probable error
d	day	J	joule	pp.	pages
dB	decibel	L	lambert	ppm	parts per million
dc	direct current	L	liter	qt	quart
˚C	degree Celsius	lb	pound	rad	radian
˚F	degree Fahrenheit	lbf	pound-force	rf	radio frequency
dia	diameter	lbf•in	pound-force inch	rh	relative humidity
emf	electromotive force	lm	lumen	s	second
eq	equation	ln	logarithm (base e)	SD	standard deviation
F	farad	log	logarithm (base 10)	sec.	section
fc	footcandle	M	molar	SWR	standing wave ratio
fig.	figure	m	meter	uhf	ultrahigh frequency
FM	frequency modulation	min	minute	UV	ultraviolet
ft	foot	mm	millimeter	V	volt
ft/s	foot per second	mph	miles per hour	vhf	very high frequency
g	acceleration	m/s	meter per second	W	watt
g	gram	N	newton	λ	wavelength
gr	grain	N•m	newton meter	wt	weight

area=unit^2 (e.g., ft^2, in^2, etc.); volume=unit^3 (e.g., ft^3, m^3, etc.)

PREFIXES

d	deci (10^{-1})	da	deka (10)
c	centi (10^{-2})	h	hecto (10^2)
m	milli (10^{-3})	k	kilo (10^3)
μ	micro (10^{-6})	M	mega (10^6)
n	nano (10^{-9})	G	giga (10^9)
p	pico (10^{-12})	T	tera (^{1012})

COMMON CONVERSIONS (See ASTM E380)

0.30480 m = 1 ft	4.448222 N = 1 lbf
2.54 cm = 1 in	1.355818 J = 1 ft•lbf
0.4535924 kg = 1 lb	0.1129848 N m = 1 lbf•in
0.06479891g = 1gr	14.59390 N/m = 1 lbf/ft
0.9463529 L = 1 qt	6894.757 Pa = 1 lbf/in^2
3600000 J = 1 kW•hr	1.609344 km/h = 1 mph

Temperature: $T_{\circ C} = (T_{\circ F}-32)\times 5/9$

Temperature: $T_{\circ F} = (T_{\circ C}\times 9/5)+32$

1. INTRODUCTION

Radio communications are essential to the operations of Federal, State, and local law enforcement and correction agencies. Effective and reliable communications systems not only enable personnel to perform their functions efficiently, but also help ensure their safety. It is, therefore, very important that all components of a radio communications system be selected and integrated to produce an effective design. Understanding the capabilities and limitations of a communications system ensures that it is used most effectively and that performance expectations are realistic.

This guide focuses on a key portion (subsystem) of the radio communications system—the antenna system. Although the antenna itself may be the most visible element of radio communications equipment, it is often the least understood. This guide defines and describes the components of the antenna system as well as the fundamentals and characteristics of the antenna itself.[1]

1.1 Scope

The theory and empiricism upon which antenna technology is based are very complex. It is not the purpose of this guide to tutor the reader in the study of electromagnetic theory. Rather, it is to provide the reader with sufficient understanding of the fundamentals, characteristics, and functions of antennas to enable him or her to develop requirements and discuss antennas with vendors, installers, repair shops, *etc.* To this end, the number of equations and references to theory are kept to a minimum, and the information is generally restricted to the kind of antennas used by law enforcement agencies.

This guide is intended for a wide audience. It is written so that the reader can study only those sections of interest. Cross-referencing is provided where needed to direct the reader to related, important information.

1.2 Organization

Section 2 of this guide provides the reader with a brief description of land mobile radio (LMR), which is the radio service used by nearly all law enforcement agencies. The frequency bands used by LMR are described. The information provided on antennas in this guide is generally limited to LMR applications and the radio frequencies used by LMR.

Section 3 begins with an overview of the major elements of a radio communications system. The function of the antenna (sub)system is described. The remainder of the section provides a brief history of the antenna and an introduction to the fundamentals of antennas and radio wave propagation. Several of the subsections are important to the understanding of antennas. These are section 3.2 on frequency and wavelength and section 3.3 on radiation principles. The reader is encouraged to review the simple, but important, concepts

[1] Certain commercial companies and their products and information are identified in this report to specify adequately the technical concepts and principles being presented. In no case does such identification imply recommendation or endorsement by the National Institute of Justice, or any other U.S. Government department or agency, nor does it imply that the sources, products, and information identified are necessarily the best available for the purpose.

in these subsections to fully understand the following sections.

Section 4 is the most important part of this guide, as it presents the engineering, or functional, characteristics of antennas. It defines gain, directivity, and radiation pattern and how these are used in a radio communications system design. These and other characteristics are also used to specify an antenna. Section 5 contains descriptions of common antennas including their electrical and radiation characteristics as well as their physical characteristics. Although there are many different kinds of antennas, the emphasis is on those antennas commonly used for LMR.

Sections 6 and 7 relate to the use of antennas within a radio communications system. Section 6 describes the transmission lines and related components needed to connect an antenna to a transmitter or a receiver, and section 7 describes the modes of radio wave propagation commonly used for LMR systems. Section 7 also discusses how an antenna pattern and propagation effects are used to achieve required geographical coverage.

The next three sections (8, 9, and 10) cover the practical aspects of developing and expressing requirements for an antenna; the installation, maintenance, and safety of antennas; and examples of some of the products and services available, respectively.

Section 11 provides the reader with a list of the relevant regulatory, standards, and professional organizations. The last two sections (12 and 13) provide reference material. Section 12 is a list of acronyms used in this guide or related to antennas. Section 13 contains the references cited in this guide.

2. LAND MOBILE RADIO

The formal title of the type of radio service used by law enforcement agencies for their radio communications is "land mobile service," and the frequency bands reserved for their use are labeled "public safety." Land mobile service is defined as "a mobile radio service between base stations and land mobile stations, or between land mobile stations," by the National Telecommunications and Information Administration (NTIA) [1][2] and the Federal Communications Commission (FCC) [2]. Another commonly used phrase for "land mobile service" is "land mobile radio" (LMR).

2.1 Users

There are two general classes of users. One class of users is radio common carrier (RCC). RCC owners build and operate LMR systems and charge a fee to third parties that actually use the system. The other class of users includes groups that meet specific requirements for LMR use. These groups include: Public Safety Radio Services, Special Emergency Radio Services, Industrial Radio Services, Land Transportation Radio Services, Radio Location Services, and Specialized Mobile Radio Services. The first group listed here, the Public Safety Radio Services, is the category that includes State and local governments, law enforcement and corrections, fire, emergency medical services, highway maintenance, and forestry conservation. Federal law enforcement and corrections agencies also belong to this category of LMR users. These Federal agencies may use some of the same frequency bands and channels as State and local agencies, but, in many cases, they use frequency bands and channel assignments unique to the Federal Government.

Most LMR user groups maintain formal associations that provide for the exchange of information within their groups and represent their members before the FCC and other official or government bodies. Those associations relevant to the law enforcement community include the Association of Public-Safety Communications Officials (APCO), the National Association of State Telecommunications Directors (NASTD), and the Telecommunications Industry Association (TIA). The first two of these represent the users, and the last represents the manufacturers of the equipment used for LMR. More details on these associations and other relevant organizations are presented in section 11.

2.2 Frequency Bands

There are a number of frequency bands allocated for use by LMR. The particular frequency ranges for these bands have been established at the international level, in plenipotentiary conferences, by the International Telecommunications Union (ITU). Administration and assignment of frequencies within the LMR bands in the United States are performed by two different government agencies. The FCC provides frequency assignments and licenses for all non-Federal users. Federal users obtain their frequency assignments through NTIA.

The LMR bands described in the following sections are subdivided for Federal use only, shared Federal and non-Federal use, and

[2] Numerals in square brackets refer to references identified in section 13.

non-Federal use only. Portions of some bands may be shared with other services such as maritime mobile, mobile satellite, and broadcast television.

2.2.1 VHF Low-Band

This band is located at 25 MHz to 50 MHz and generally uses channels 20 kHz wide. Communications ranges can be the greatest in this band; however, the radio signals do not reflect effectively off hills, buildings, and other surfaces, so there may be dead spots within the general area of coverage of a base station. These frequencies, especially at the lower end of the band, are subject to ionospheric “skip,” which can carry a signal very long distances (and cause interference to other users). This band also has the highest level of ambient noise, which reduces the performance of receivers operating in this band compared to other, higher frequency-bands.

2.2.2 VHF High-Band

This band is located at 150 MHz to 174 MHz and uses channels 25 kHz or 30 kHz wide. Adjacent channels may be separated by 12.5 kHz to 15 kHz for geographically separated systems. Radio signals in this band have a shorter propagation range, experience less noise than those in the VHF low-band, and are not subject to ionospheric “skip.” Diffraction over hills and around other obstacles reduces dead areas of coverage.

2.2.3 UHF Bands

The first UHF band is located at 406 MHz to 420 MHz and is designated for Federal usage. The second band is located at 450 MHz to 470 MHz and is designated for non-Federal usage. The last band, from 470 MHz to 512 MHz, shares spectrum with UHF television channels 14 through 20 in a few major urban areas. Channels in all three UHF bands are 25 kHz wide. The propagation range in the UHF band is even less than that found in the VHF high-band; however, the radio signals easily reflect off hills and buildings, so dead areas are generally very small.

2.2.4 700 MHz Band

New bands from 764 MHz to 776 MHz and 794 MHz to 806 MHz have been proposed by the FCC. These new channels would be converted from TV channels 63–64 and 68–69 to Public Safety use. The channels would be either narrowband for voice plus low-speed data or wideband (up to 150 kHz) for high-speed data.

2.2.5 800/900 MHz Band

The portion of the radio spectrum from 806 MHz to 940 MHz is apportioned among many services, including cellular telephone, paging, nonpublic safety, and conventional and trunked public safety. Federal Government users, however, have no authorizations in this spectrum. Channels for public safety are reserved in blocks that are generally 25 kHz wide. These blocks reside in several locations within this portion of the radio spectrum. These radio signals reflect off hills, buildings, vehicles, *etc*., well enough that dead areas are nearly nonexistent. The propagation range for this band is shorter than for the UHF bands.

2.3 Rules and Regulations

2.3.1 General

In the United States, the FCC allocates different bands of the radio-frequency spectrum to different entities for a wide variety of commercial and private applications [2]. The NTIA performs this function for the Federal Government. In recent years, with the proliferation of portable phones and other mobile communications devices, the FCC and the NTIA have received an increasing number of requests for an ever-dwindling amount of spectrum available for allocation.

One way that the FCC and NTIA attempt to maximize spectrum usage is to assign the right to transmit over the same channel to different commercial or private groups that are located in different geographic regions, so that their signal coverage areas will not overlap. Consideration is also given when assigning adjacent channels, so signals from one transmission channel will not affect adjacent channels.

Further description of the allocation process and the most recent listing of allocations can be found in the *NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management* [1] and the *Code of Federal Regulations* [3] pertaining to telecommunications.

2.3.2 Future Options

At the present time, LMR bands are crowded and channel assignments can be difficult to obtain in some areas of the country. For this reason, work is underway to develop new, spectrally efficient modulation and signal-processing methods and improved techniques to share existing channels. Historically, this problem has been addressed by making narrower channels within a band. Frequency-modulation (FM) systems have been improved to allow them to operate in bandwidths as small as 12.5 kHz. Further improvement requires different modulation methods, but care must be taken in choosing and standardizing the modulation method and channel widths to ensure interoperability among different systems and equipment from different manufacturers.

New LMR systems conforming to the “Project 25" standard [4] use narrowband modulation techniques and channel-sharing methods (called trunking). These new digital modulation methods will be able to use channels as narrow as 6.25 kHz. Trunking techniques will accommodate two, three, or more times as many users for a given number of channels.

3. ANTENNA FUNDAMENTALS

The antenna is often the most visible element of a radio system. The sizes and shapes of the conductors that comprise the antenna determine the directional characteristics of the electromagnetic (radio) waves it radiates. However, the antenna cannot be considered independently. Additional elements, such as the transmission line, duplexers, matching networks, *etc.*, must be considered as part of the *antenna system*.

The full description of the interaction of an antenna with its surrounding environment is based on very complex mathematics, but its function in a radio system is quite simple. Figure 1 shows the key elements of a radio communications system. When an antenna is used for transmitting, it converts electrical signals, delivered by a transmission line, from a transmitter into propagating electromagnetic waves. When an antenna is used for receiving, it converts electromagnetic waves back into electrical signals that are delivered by a transmission line to a receiver for processing. In fact, the same antenna (used for both transmitting and receiving) is often attached to a transmitter and a receiver using either a *duplexer* or a *transmit/receive* (XMT/RCV) *switch*. A duplexer allows one antenna to be used by both the transmitter and receiver at the same time (see sec. 6.3), and a transmit/receive switch connects the antenna to either the transmitter or receiver.

3.1 History of the Antenna

Over a century has elapsed since James Clerk Maxwell [5] formulated his celebrated equations that provide the foundation of classical electromagnetism. By means of these equations, Maxwell was able to predict the existence of electromagnetic waves which, 20 years later in 1887, were confirmed experimentally by Heinrich Hertz [6]. Hertz constructed a center-driven wire about 60 cm long, terminated at each end by a 40 cm square metal plate. Driven by a spark-gap generator (broadband source), this antenna resonated at about 50 MHz and effectively generated and radiated

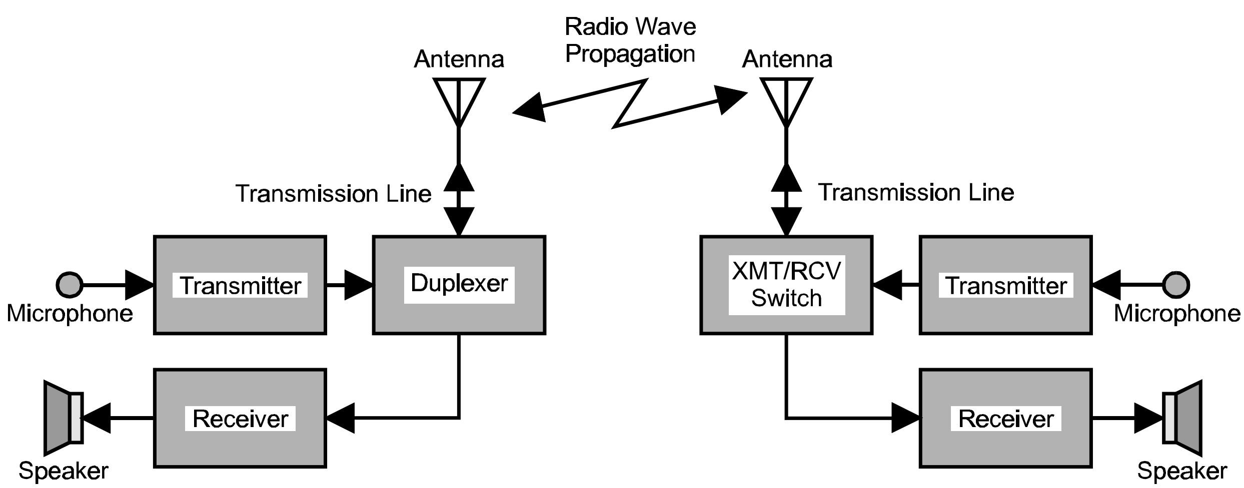

Figure 1. Elements of a radio system

electromagnetic waves. He detected those waves using a loop of wire, 35 cm in radius, with a very small gap where he could observe a spark. Although a number of researchers became interested in this new phenomenon, it was Gugliermo Marconi who, in 1897, described and then demonstrated a complete system for the *transmission of signals*. On December 12, 1901, the first transatlantic communication was achieved. The transmitting antenna in Cornwall, England, was a fan-like structure of 50 copper wires supported by a horizontal wire stretched between two poles about 45 m high and 65 m apart. The receiving antenna in Newfoundland was comprised of copper wires supported by kites. By 1907, commercial, transatlantic telegraph services had been established [7].

It is interesting to note that the original, commonly used term for a signaling system that uses the phenomenon of electromagnetic waves was "wireless." Although the term "radioconductor" (a contraction of radiation conductor) appears as early as 1897, the term "radio" does not emerge until later. The Radio Ship Act of 1910 contains the terms "radio" and "radio-communication" but not "wireless." In 1912, the U.S. Navy directed the use of the term "radio" in place of "wireless" [8].

3.2 Frequency and Wavelength

A propagating electromagnetic wave exists because of the fundamental interdependence of the electric and magnetic fields that comprise it. An electric field that changes with time produces a magnetic field whose strength is determined by the *rate of change* of the electric field. And, in complementary fashion, a magnetic field that changes with time produces an electric field whose strength is determined by the *rate of change* of the magnetic field. This means that the energy contained in, and transmitted by, the radio wave is shared by the two fields.

When transmitting, the electrical current on an antenna produces the magnetic field, and the voltage on that antenna produces the electric field. Similarly, when receiving, an electromagnetic wave incident on the antenna produces electrical current and voltage. If these currents and voltages have a sinusoidal time dependence (sine or cosine wave), then several very important, fundamental phenomena occur. The first derivative (rate of change) of a sine wave is another sine wave shifted in time by one quarter of the period of the first sine wave. This means that if the changing electric field in the radio wave is sinusoidal, then so is the magnetic field. These two sinusoidal time-varying fields, in effect, regenerate each other as they travel. This is called wave propagation.

The frequency of a sine wave is expressed as the number of cycles per second or *hertz*. The period of the wave is the reciprocal of its frequency and is expressed in seconds. The wavelength is the length of one cycle of the traveling wave in space, or the distance the wave travels during one period. The relationship between frequency and wavelength is

$$\lambda = \frac{c}{f} \qquad (1)$$

where λ is the wavelength (m), c is the speed of light (2.9979×10^8 m/s), and f is the frequency (Hz). A practical, approximate version of this equation is

$$\lambda \approx \frac{300}{f} \qquad (2)$$

where λ is in meters and f is in megahertz.

3.3 Radiation Principles

The important characteristics of an antenna are its radiation properties, such as *gain*, *directionality*, and *polarization*; and the electrical property, *input impedance*. These and other characteristics can be determined theoretically, or they can be obtained by measurement. In practice, both theory and measurement are used to design or evaluate an antenna.

The remainder of this section is necessary to the understanding and usefulness of section 4, Antenna Characteristics. Although based in electromagnetic theory, these fundamental principles are not complicated and they are essential to an understanding of antennas.

3.3.1 What Is an Antenna?

An antenna is a device that provides suitably localized and oriented paths for oscillating electric currents. The sizes and shapes of the conductors that comprise the antenna determine the directional characteristics of the radio waves it radiates. A transmitting antenna converts electrical currents, delivered by the transmission line from a transmitter, into propagating radio waves, and a receiving antenna converts radio waves back into electrical currents that are delivered by a transmission line to a receiver.

3.3.2 Reciprocity

The theoretical determination of an antenna's characteristics is usually accomplished by treating the antenna as a transmitting device. However, under most conditions, the antenna characteristics are exactly the same when it is used as a receiving device. If the antenna is *linear* (*i.e.*, it contains neither active elements nor nonlinear components such as ferrites), then the *principle of reciprocity* holds. This principle was first described by the famous mathematician Lord Rayleigh [9]. The principle of reciprocity means that an antenna will have exactly the same characteristics whether it is used for transmitting or receiving. So, if a particular characteristic of an antenna is obtained by measurement while using the antenna for reception, then it is known that the same antenna will have exactly the same characteristic when used for transmission.

3.3.3 Radiated Waves and the Near Field

The electromagnetic field produced by an antenna is quite complex near the antenna, and it can be described as having several components. Only one of these actually propagates, or travels though space. This component is called the radiated field, radiated wave, or radio wave. The propagation of this radiated field, or radio-wave propagation, is usually treated as a separate topic. The strength of the radiated field does decrease with distance, as it must, since the energy must spread as it travels. Some knowledge of propagation is useful in understanding antennas or in choosing an antenna to meet certain requirements, such as coverage—the area over which a radio wave has sufficient strength to be useful.

Section 7 presents a brief overview of radio-wave propagation.

The other components of the electromagnetic field remain near the antenna and do not propagate. There are generally two other components: the static field and the induction field. Even though they do not propagate, their strength decreases very rapidly with distance. The entire field—all of the components—near the antenna is called the *near field*. In this region, approximately one wavelength in extent, the field strength can be relatively high and pose a hazard to the human body. See section 9.5.4 for more information on this *radiation hazard*.

3.3.4 Plane Waves

The radiated wave, as with all electromagnetic waves including light, is composed of an electric field and a magnetic field. For most cases, the field lines, and the vectors that are used to illustrate them, are at a right angle to each other and to the direction of propagation, as shown in figure 2.

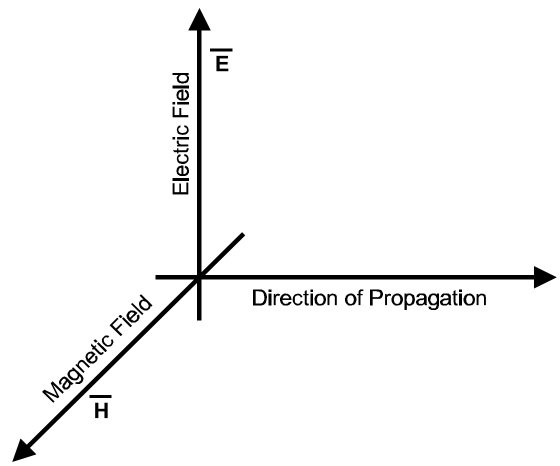

Figure 2. The propagation of a plane electromagnetic wave

At large distances from the antenna, say beyond ten wavelengths, the radiated field is essentially a *plane wave*. This means that there is no curvature of the field lines.

3.3.5 Wave Polarization

The polarization of a wave, by definition, is simply the orientation of the electric field vector. The plane wave depicted in the illustration of figure 2 is vertically polarized. For nearly all cases encountered in LMR, the polarization of the wave does not change as it propagates. This is called *linear polarization*, and the two most common examples in practice are vertical or horizontal polarization. Other polarizations include circular, where the electric field vector (and the magnetic field vector) rotate as the wave travels.

4. ANTENNA CHARACTERISTICS

In a radio communications system, an antenna has two basic functions. The primary function is to radiate, as radio waves, the RF signals from the transmitter, or to convert radio waves into RF signals for processing by a receiver. The other function is to direct the radiated energy in the desired direction or directions, or to be "sensitive" to reception from the desired direction or directions. Another, often overlooked, aspect of an antenna's directional properties is the suppression of radiation in undesired directions, or the rejection of reception from undesired directions.

The directional characteristics of an antenna are fundamental to an understanding of the antenna and how it is used in a radio communications system. These interrelated characteristics include *gain*, *directivity*, *radiation* (*antenna*) *pattern*, and *polarization*. Other characteristics such as *beamwidth*, *effective length*, and *effective aperture* are derived from the four listed above. *Terminal* (input) *impedance* is one other characteristic that is of fundamental importance. It is necessary to know the impedance of an antenna in order to efficiently couple the transmitter's output power into it, or to efficiently couple the power from it into the receiver. All of these antenna characteristics are a function of frequency.

4.1 Gain and Directivity

The gain of an antenna is the radiation intensity[3] in a given direction divided by the radiation intensity that would be obtained if the antenna radiated all of the RF power delivered to it equally in all directions [10, 11]. Note that this definition of gain requires the concept of an isotropic radiator; that is, one that radiates the same power in all directions. Examples of nondirectional sources can be achieved (at least approximately) with sound and light; these are sometimes called point sources.

An isotropic antenna, however, is just a concept, because all practical radio antennas must have some directional properties. Nevertheless, the isotropic antenna is very important as a reference. It has a gain of unity (g = 1 or G = 0 dB) in all directions, since all of the power delivered to it is radiated equally well in all directions.

Although the isotrope is a fundamental reference for antenna gain, another commonly used reference is the dipole. In this case the gain of an ideal (lossless) half-wavelength dipole is used. Its gain is 1.64 (G = 2.15 dB) relative to an isotropic radiator.

The gain of an antenna is usually expressed in decibels (dB). When the gain is referenced to the isotropic radiator, the units are expressed as dBi; but when referenced to the half-wave dipole, the units are expressed as dBd. The relationship between these units is

$$G_{dBd} = G_{dBi} - 2.15 \quad \text{dB} \quad . \qquad (3)$$

Directivity is the same as gain, but with one difference. It does not include the effects of power lost (inefficiency) in the antenna

[3] Radiation intensity is defined as the power density in terms of power per unit solid angle.

itself. Recall that the definition of gain is based on the power delivered to (and accepted by) the antenna. In practice, some of that power is lost in the antenna due to ohmic losses (heating) in the elements, leakage across insulators, *etc.* If an antenna were lossless (100 % efficient), then the gain and directivity (in a given direction) would be the same.

4.2 Radiation Pattern

The *radiation pattern* (also called *antenna pattern*) is a representation of the gain of an antenna for all directions. Since this is a three-dimensional description of the power density, it is difficult to display or use. It is common to display or plot cross-sections of it. Figure 3 shows the radiation pattern of a vertical half-wavelength dipole in the horizontal plane and a vertical plane. As one can see in this figure, the patten in the horizontal plane has no structure. This antenna has constant gain versus azimuth. On the other hand, the pattern in a vertical plane shows that the antenna has maximum gain in the horizontal plane and no radiation in the directions coincident with the axis of the antenna. Therefore, one can now visualize the three-dimensional pattern as a torus (doughnut shaped).

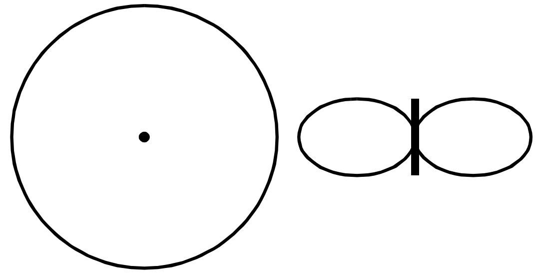

Figure 3. The horizontal-plane and vertical-plane patterns of a vertical half-wavelength dipole

Often, the direction is not specified when referring to an antenna's gain. In this case, it is assumed that the gain's direction is the direction of maximum radiation—the maximum gain for the antenna. An associated pattern then will present values relative to that maximum gain.

4.2.1 Lobes and Nulls

The regions of a pattern where the gain has local maxima are called *lobes,* and those places where the gain has local minima are called *nulls*. The vertical plane "cut" for the half-wave dipole (fig. 3b) has two lobes and two nulls. Figure 4 shows several other examples. A complex antenna pattern may have many lobes and nulls in both the horizontal-plane and vertical-plane patterns. The lobe with the greatest gain is called the *main lobe* or *main beam* of the antenna. If a single value of gain is given for an antenna, it is assumed to be the main lobe or *main beam gain*.

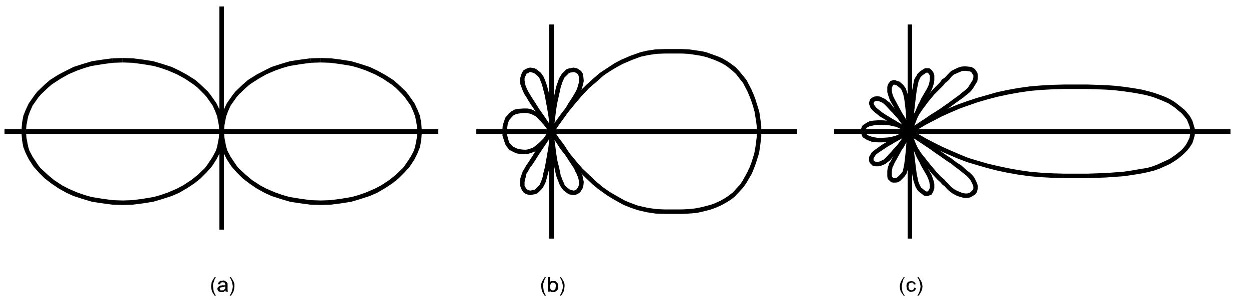

Figure 4. Vertical-plane radiation patterns [12] showing increasing complexity of lobes and nulls

4.2.2 Beamwidth

Beamwidth is an angular measure of the *main lobe* (or main beam) in either (or both) the horizontal-plane or vertical-plane pattern [11]. There are several definitions for beamwidth, including: *half-power* or *3 dB beamwidth*, *10 dB beamwidth*, and *first-null beamwidth.* The 3 dB beamwidth is the angular extent about the maximum value of gain for which the gain is 3 dB below the maximum. First-null beamwidth is the angular extent about the maximum value of gain of the first occurring local minima in the pattern. The half-power, or 3 dB, beamwidth is most commonly used.

4.3 Antenna Polarization

The term *polarization* has several meanings. In a strict sense, it is the orientation of the electric field vector E at some point in space. If the E-field vector retains its orientation at each point in space, then the polarization is linear; if it rotates as the wave travels in space, then the polarization is circular or elliptical. In most cases, the radiated-wave polarization is linear and either vertical or horizontal. At sufficiently large distances from an antenna, *e.g.*, well beyond 10 wavelengths, the radiated, far-field wave is a plane wave (see sec. 3.3.4).

The term polarization is often applied to the antenna itself. In this sense, the *polarization of the antenna* is the polarization of the plane wave it radiates. Based on the principle of reciprocity (see sec. 3.3.2), this is true for a receiving antenna, as well. For example, if a receiving antenna is vertically polarized, this means that a vertically polarized, incoming wave will produce maximum output from that antenna. If the incoming wave were polarized at some other angle, only the vertical component would be detected by the antenna. Ideally, a horizontally polarized incoming wave would not be detected at all by a vertically polarized antenna. Vertical polarization is used for most LMR applications.

4.4 Antenna Terminal Impedance

There are three different kinds of impedance relevant to antennas. One is the *terminal impedance* of the antenna, another is the *characteristic impedance* of a transmission line, and the third is *wave impedance*. Antenna terminal impedance is discussed in this section. Transmission line characteristic impedance is discussed in section 6, and wave impedance is the ratio of the electric field strength to the magnetic field strength of a propagating wave (see sec. 3.2 and sec. 3.3.4).

Terminal impedance is defined as the ratio of voltage to current at the connections of the antenna (*i.e.*, the point where the transmission line is connected). The complex form of Ohm's law defines impedance as the ratio of voltage across a device to the current flowing through it. The terminal impedance is expressed mathematically as

$$Z = \frac{V}{I} \tag{4}$$

where Z is the impedance, in ohms, V is the voltage, in volts, and I is the current, in amperes, at the antenna terminals for a given frequency. Each of these variables can be expressed as a complex number, each with real and imaginary parts. Such complex numbers can also be expressed by using a magnitude and phase angle—this is called *phasor* notation.

The real part of the impedance is called the resistive component, and the imaginary part is called the reactive component. This is often expressed as

$$Z = R + \mathrm{j}X \tag{5}$$

where R is the resistive (real) component, X is the reactive (imaginary) component, and $\mathrm{j} = \sqrt{-1}$.

The most efficient coupling of energy between an antenna and its transmission line occurs when the characteristic impedance of the transmission line and the terminal impedance of the antenna are the same and have no reactive component. When this is the case, the antenna is considered to be *matched* to the line.

Matching usually requires that the antenna be designed so that it has a terminal impedance of about 50 Ω or 75 Ω to match the common values of available coaxial cable. A half-wave dipole can be shortened slightly to achieve this. For other antennas, it can be difficult to remove (reduce to zero) the reactive component. In these cases, a matching network is often made part of the antenna to change its complex terminal impedance into something that better matches a transmission line.

The resistive part R of the terminal impedance is the sum of two components and is expressed in ohms,

$$R = R_r + R_d \quad . \tag{6}$$

The *radiation resistance* R_r is the "effective load" that represents the power radiated by that antenna as radio waves, and the dissipative resistance R_d is the "load" into which power is lost. The efficiency of an antenna is the ratio of the power radiated to the total power delivered to the antenna. It can be expressed as

$$\text{Efficiency} = \frac{I^2 R_r}{I^2 R} = \frac{R_r}{R} \quad . \tag{7}$$

As discussed in section 4.1, the dissipative losses are due to ohmic losses (heating) in the antenna elements, leakage across insulators, and similar effects. Furthermore, it should be noted that the efficiency of an antenna can also be expressed as the ratio of the gain to the directivity (for a given direction).

4.5 Voltage Standing Wave Ratio

The *standing wave ratio* (SWR), also known as the *voltage standing wave ratio* (VSWR), is not strictly an antenna characteristic, but is used to describe the performance of an antenna when attached to a transmission line. It is a measure of how well the antenna terminal impedance is matched to the characteristic impedance of the transmission line. Specifically, the VSWR is the ratio of the maximum to the minimum RF voltage along the transmission line. The maxima and minima along the lines are caused by partial reinforcement and cancellation of a forward-moving RF signal on the transmission line and its reflection from the antenna terminals.

If the antenna terminal impedance exhibits no reactive (imaginary) part and if the resistive (real) part is equal to the characteristic impedance of the transmission line, then the antenna and transmission line are said to be matched. If this is true, then none of the RF signal sent to the antenna will be reflected at its terminals. There is no standing wave on the transmission line and the VSWR has a value of one. However, if the antenna and transmission line are not matched, then some fraction of the RF signal sent to the antenna is reflected back along the transmission line. This causes a standing wave, characterized by maxima and minima, to exist on the line. In this case, the VSWR has a value greater than one.

The VSWR is easily measured with a device called an *SWR meter*. It is inserted in the transmission line and directly gives a value for the VSWR. At a VSWR value of 1.5, approximately 4 % of the power incident at the antenna terminals is reflected. At a value of 2.0, approximately 11 % of the incident power is reflected. VSWR values of 1.1 to 1.5 are considered excellent, values of 1.5 to 2.0 are considered good, and values higher than 2.0 may be unacceptable.

As stated above and elsewhere, an ideal match between the antenna and transmission line is desired; but this can often be achieved only for a single frequency. In practice, an antenna may be used for an entire frequency band, and its terminal impedance will vary across the band. In an antenna specification, either the impedance versus frequency across a band is given or the VSWR versus frequency is given.

4.6 Effective Length and Effective Area

The *effective length* and the *effective area* (also called *effective aperture*) are alternative ways of expressing the gain of an antenna. These characteristics are most useful and meaningful when the antenna is used for receiving. Of course, due to the principle of reciprocity, these characteristics are the same if the antenna is used for transmitting.

The effective length defines the ability of an antenna to produce a voltage at its terminals from an incident electric field. It is defined as

$$\ell_e = \frac{V}{E} \tag{8}$$

where ℓ_e is expressed in meters, V is the open circuit voltage in volts, and E is the electric field strength in volts/meter. This definition assumes that the polarization of the incident field and the antenna are the same. The effective length can also be computed from the gain and the radiation resistance.

Effective area, or aperture, is more commonly used than effective length. It is defined as

$$A_e = \frac{P_r}{p} \tag{9}$$

where P_r is the power available at the terminals of the antenna in watts, and p is the power density of the incident wave in watts per square meter. The relationship between effective area and gain is

$$A_e = \frac{\lambda^2}{4\pi} g \quad . \tag{10}$$

4.7 Bandwidth

Bandwidth is the difference between two frequencies, or the frequency range, within which the performance of an antenna is acceptable. In other words, one or more characteristics (*e.g.,* gain, pattern, terminal impedance) have acceptable values between the bandwidth limits. For most antennas, gain and pattern do not change as rapidly with frequency as the terminal impedance does, so the latter is often used to describe the bandwidth of an antenna.

VSWR (see sec. 4.5) is a measure of the effect of mismatch between an antenna's terminal impedance and the transmission line characteristic impedance. Since the transmission line characteristic impedance hardly changes with frequency, VSWR is a useful, practical way to describe the effects of terminal impedance and to specify an antenna's bandwidth. For example, an antenna specification may give a plot of the VSWR across some frequency band. It will likely have a minimum value at about the middle of the band. Another way of specifying the bandwidth is a statement of the maximum VSWR within a band.

Half-wave dipoles, and similar antennas, have a narrow bandwidth. Other antennas, like the log-periodic, are designed specifically to be broadband.