7. RADIO WAVE PROPAGATION

The propagation of radio waves through space (and the atmosphere) is the essential phenomenon exploited by a radio communications system. As described earlier (sec. 3), this phenomenon has been studied extensively using theoretical and empirical methods. The simplest mode of propagation occurs between two point-sources in free space—the ideal situation.

Radio-wave propagation, in realistic situations, is affected by reflections from the earth, scattering by particles, diffraction over hills, and bending due to atmospheric refractivity. The study of propagation has led to models that can be used to predict the field strength (and/or power density) expected at a specific receiver location of a radio wave radiated from a distant transmitter location.

7.1 Transmission Loss and the Power Budget

The concept of *transmission loss* is used to quantify the effects of radio wave propagation in the analysis and engineering of radio communications systems. It is defined as the ratio of power delivered to the terminals of the transmitter antenna to the power available at the terminals of the receiver antenna. The transmitter and receiver antenna gains are implicitly included in this definition. In practice, this is not useful, so the concept of *basic transmission loss* is used. It does not include the antenna gains. Basic transmission loss L_b is defined as the ratio of the power delivered to a lossless isotropic antenna at the transmit location to the power available at the terminals of a lossless isotropic antenna at the receive location.

With this definition of basic transmission loss, a power budget can be developed. This is shown graphically in figure 34, which shows the effects of the major elements in the radio link.

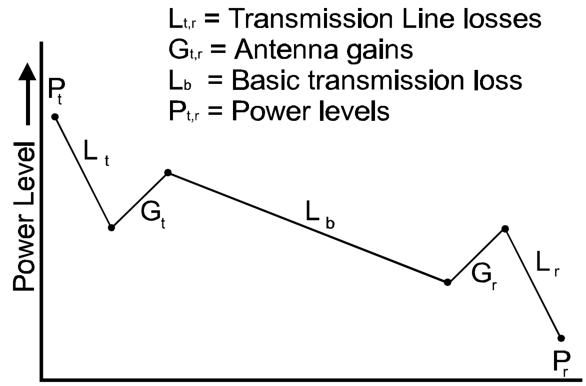

Figure 34. Gains and losses as described in the power-budget equation

It begins with the power output of the transmitter P_t in decibels relative to some reference (if referenced to 1 W, this is expressed as dBW). The loss, in decibels, due to the transmitter transmission line L_t is subtracted from P_t. Then the transmitter antenna gain G_t is added. The basic transmission loss L_b is subtracted. Then at the receive end of the link, the receive gain G_r is added; and the receiver transmission line loss L_r is subtracted to arrive at the power delivered to the receiver input P_r.

Expressed as an equation, the power budget is

$$P_r = P_t - L_t + G_t - L_b + G_r - L_r \, . \quad (11)$$

The received power is in the same units as those used to express the transmitted power.

For example, a transmit power of 25 W, expressed in decibels, would be 10 $\log_{10}$ (25) or 14 dBW. The result is that the power available at the receiver input P_r is expressed in the same units (dBW in this example).

7.2 Free-Space Basic Transmission Loss

The transmission loss between two lossless isotropic antennas in free space[4] is a hypothetical, but very useful, propagation model. It can be used as a "first estimate" in radio link design or a "best case" value for transmission loss over any real, terrestrial path.

The free-space basic transmission loss L_{bf} is very easy to calculate. Since the transmit antenna is considered to be a lossless isotrope (and the transmission line is considered to be lossless as well), all of the transmitter power is radiated equally in all directions. At a distance d selected to be much greater than the wavelength λ, the radiated power density (expressed in watts per square meter) is simply the transmitter power divided by the area of a sphere with radius d, as follows:

$$p = \frac{P_t}{4\pi d^2} \quad . \tag{12}$$

Now, looking at the receive side of the link, the signal power output P_r in watts, of a lossless, isotropic receive antenna can be computed using equation 9. It is the product of that antenna's effective area A_e times the power density p of the incident wave as follows,

$$P_r = A_e \, p \quad . \tag{13}$$

Using equation 10, the effective area, in square meters, of a lossless isotropic antenna ($g = 1$) is

$$A_e = \frac{\lambda^2}{4\pi} \quad . \tag{14}$$

Substituting equations 12 and 14 into equation 13, the result is

$$P_r = \frac{\lambda^2}{4\pi} \cdot \frac{P_t}{4\pi d^2} \quad . \tag{15}$$

Rearranging this equation to form the definition of L_{bf} as the ratio of P_t to P_r (see sec. 7.1),

$$L_{bf} = \frac{P_t}{P_r} = \left(\frac{4\pi d}{\lambda} \right)^2 \quad \text{dB} \quad . \tag{16}$$

In decibels, this equation becomes,

$$L_{bf} = 10 \log_{10} \left(\frac{4\pi d}{\lambda} \right)^2 \quad \text{dB} \quad . \tag{17}$$

By converting wavelength to frequency using equation 1 and taking the logarithm of the terms in parentheses, a very practical version of this equation results.

$$L_{bf} = 20 \log_{10} d + 20 \log_{10} f + 32.45 \quad \text{dB} \quad . \tag{18}$$

where d is expressed in kilometers and f is expressed in megahertz.

This last equation is the *propagation model for free-space, basic transmission loss*. It predicts a value of basic transmission loss under a set of assumptions (*i.e.*, lossless

[4] Free space is a theoretical concept of space devoid of all matter. In practice, free space implies remoteness from material objects that could influence the propagation of electromagnetic waves.

isotropic antennas located in free space). As an example of how to use this model and the power-budget equation, consider a radio link 10 km long operating at 400 MHz. For this link, assume that the transmit antenna has a gain of 10 dB, the receive antenna has a gain of 3 dB, and that both transmit and receive transmission line losses are 1 dB. The transmitter power is assumed to be 20 W (13 dBW).

The basic free-space transmission loss is first computed as

$$\begin{aligned} L_{bf} &= 20 \log_{10}(10) + 20 \log_{10}(400) + 32.45 \\ &= 20 + 52.04 + 32.45 \\ &= 104.49 \text{ dB} \quad . \end{aligned} \tag{19}$$

Then, using the power budget equation 11, we find that

$$\begin{aligned} P_r &= 13 \text{ dBW} - 1 \text{ dB} + 10 \text{ dB} - 104.49 \text{ dB} + 3 \text{ dB} - 1 \text{ dB} \\ &= -80.49 \text{ dBW} \\ &= -50.49 \text{ dBm} \quad . \end{aligned} \tag{20}$$

This result shows a receive power of about one one-hundredth of a microwatt, or about nine orders of magnitude less than the transmit power. At this level, it is a strong receive signal. An actual radio link, over varied terrain, may have a larger measured transmission loss by 5 dB to 20 dB. The transmission loss over a realistic link will also vary with time.

7.3 Terrestrial Propagation

A variety of natural and man-made objects and phenomena will affect the radio signal as it propagates from the transmitter to the receiver. Some of these effects are described in the following subsections. Although it is important for the reader to be familiar with these concepts, it is unnecessary for the reader to determine the exact extent that each effect affects the antenna system. Several computer models are available that provide relatively accurate propagation predictions. Such models are described in section 7.4.

7.3.1 Effects of Earth

The Earth acts as a reflecting surface for those waves that radiate from an antenna at angles lower than the horizon. Waves that strike the Earth are reflected along the same direction of travel, at the same angle as the angle of incidence. The illustration in figure 35 shows how waves propagate over both direct and reflected paths to reach a distant location.

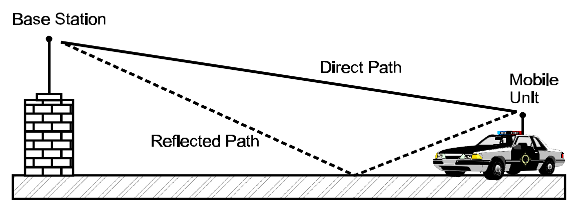

Figure 35. A propagation path illustrating direct and reflected rays

The reflected waves combine with the direct waves with a variety of results (*i.e.*, they enhance or cancel each other to some degree). Some of the factors that cause this variety are the height of the antenna, the orientation of the antenna, the length of the antenna, and the characteristics of the ground reflecting the wave. As part of the wave strikes the ground and reflects forward, that part of the wave will take a slightly longer time to arrive at the receiver.

At some reflection angles, the direct wave and reflected wave will arrive almost in phase (*i.e.*, the amplitude of each wave will be at its maximum at the same time). When this happens, the power of the received wave is approximately twice that of the direct wave. At some angles, the reflected wave is exactly out of phase with the direct wave, essentially nullifying the wave. This is known as *cancellation*. At other angles, the resultant wave will be somewhere in between.

As radio waves strike a radio-opaque object, some of the signal will be reflected in directions away from the receiver. Some of the signal will be absorbed by the object.

The waves that strike the edges of the object, however, will be diffracted into the shadow of the object. To a receiver positioned within such a shadow, the object's edge will seem like another source. This can cause interference with the original signal or provide signals to areas that should not receive them. This phenomenon is shown in figure 36.

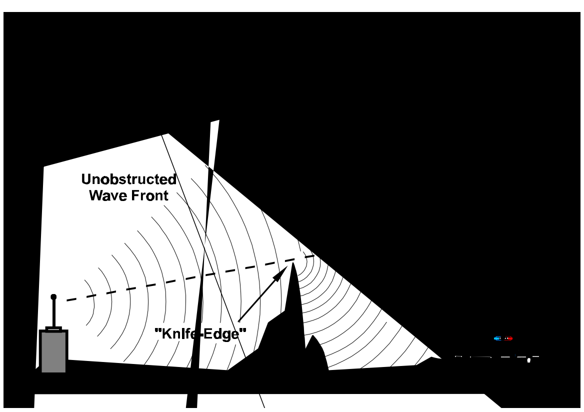

Figure 36. An example of diffraction

7.3.2 Coverage

The area over which the signal can be detected is called the *coverage* area for the antenna. The coverage area is often displayed as contours on a two-dimensional drawing or on a map.

A radiation pattern is not the same thing as a coverage area, although they are related. The radiation pattern for an antenna is a gain factor, in every direction away from the antenna, and is a function *only* of the antenna design.

The coverage area for an antenna is the area over which a signal, of predetermined strength (or greater), can be received. The coverage area is a function of the transmit power, antenna gain, radiation pattern, noise, and propagation factors related to the environment.

7.3.3 Noise and Interference

All things emit some radiation at all frequencies. In most cases, for most objects, the level of this continuous radiation, at any given frequency, is small and of little concern. This radiation is called *noise*. The most common sources of noise for a radio receiver are:

- Atmospheric and galactic noise.
- Noise from the first amplifier in the receiver.
- Man-made noise (motors, flourescent lights, *etc.*).

When a radio receiver is far enough away from a transmitter (or in an antenna pattern *null* where reception is difficult), the strength of the transmitted signal is low enough that ambient radiation noise from other objects or transmissions in the area can obscure the desired signal. When the strength of a received signal is less than the strength of the ambient noise for that frequency, the signal is said to be “lost in the noise.”

Ambient noise for a specific transmission is usually measured at the transmission frequency.

Interference is the term for unwanted signals, generated from other transmitters, that interfere with clear reception of the intended signal. Interference is not technically included under the definition of noise, although slang usage of the term “noise” includes any unwanted signals.

7.3.4 Terrestrial Propagation Models

Radio-wave propagation in the terrestrial environment is an enigmatic phenomenon whose properties are difficult to predict. This is particularly true for LMR applications where terrain features (hills, trees, buildings, *etc.*) and the ever-changing atmosphere provide scattering, reflection, refraction, and diffraction obstacles with dimensions of the same order of magnitude as the wavelengths.

Some models are general and some are more specialized. An example of the former is a model that would predict radio coverage areas in “generic” urban areas or “generic” rural areas, without regard to specific terrain profiles. One of these generalized models is the Okumura-Hata model [16]. Models such as the Okumura-Hata model are based on extensive collections of empirical measurements.

Other more sophisticated computer programs predict transmission loss, and account for the time and location variability of that loss, over defined terrain profiles. These terrain profiles are compiled from terrain-elevation data tabulated by agencies such as the Defense Mapping Agency and the U.S. Geological Survey. One such computer program, written and maintained by the U.S. Department of Commerce’s Institute for Telecommunication Sciences (ITS), is the Communication Systems Performance Model (CSPM) [17]. This program is based on the ITS Irregular Terrain Model [18].

Usually, manufacturers and vendors of radio and antenna systems and components have computer programs similar to CSPM to assist customers in defining radio-coverage areas. Private-industry radio-engineering consultants also have computer programs like CSPM to perform radio-coverage analysis for customers. Alternatively, agencies can access CSPM on a fee-reimbursable basis through the ITS Internet site[5].

7.4 Co-Site Analysis

Intermodulation (IM) *interference* (*i.e.*, “intermod”) and *receiver desensitization* are detrimental to the performance of co-sited repeaters and base stations. There are several different ways intermod *interference* can be generated. One way is when sufficiently large power from a transmitter enters into the final output power stage of another transmitter. This may occur when, for example, the transmitters are connected to a combiner junction and the combining cavity/isolators of the affected transmitter do

[5] *http://flattop.its.bldrdoc.gov/tas.html*.
For additional information, contact the Institute for Telecommunication Sciences at 325 Broadway (ITS.E), Boulder, Colorado 80305–3328, Telephone 303–497–5301.

not provide sufficient rejection between transmitters.

Intermodulation may also arise when several transmitting antennas are located in very close proximity to each other, such as multiple omni-directional antennas on a building rooftop. In these situations, mixing of signals may occur between the offending transmitter(s) and the desired signal, thereby generating new signals in the victim transmitter, at frequencies determined by the intermod products. These intermod signals will be emitted by the victim transmitter.

Other ways that intermod can occur are by the mixing of signals from two or more transmitters in the front-end of a receiver. Off-frequency signals strong enough to overcome the suppression of bandpass cavities and preselector filters may saturate the nonlinear first or second intermediate frequency (IF) mixers of the victim receiver, creating intermod products which adversely affect receiver performance.

External intermod can also be created in elements such as corroded antenna guy wires, anchor rods, and even chain link fences. As strong signals impinge upon these items, the corroded objects act as diodes and detect the signals, mix them, and passively reradiate the energy at the intermod product frequencies.

8. ANTENNA SYSTEM REQUIREMENTS AND DESIGN

The selection of a particular antenna system for use in a radio communications system is one of many interrelated decisions that must be made to meet the system-level requirements for a complete LMR system. Other system-level decisions include the number and locations of base and repeater stations, the antenna heights, and the transmitter powers.

Selecting the appropriate antennas for vehicular and hand-held units is a much simpler process than selecting the appropriate antennas for fixed stations. Although there are exceptions, the whip antenna is, essentially, the only practical antenna design for vehicular and hand-held radios. The most important aspect for vehicular antennas has to do with *where* it is mounted on the vehicle. The best location for vehicular antennas is in the middle of the roof. This is the highest point and presents the flattest and most symmetric ground plane to the antenna, both important factors to optimize communications range and performance. Vehicular obstructions, such as the light bar on law enforcement vehicles, will, however, distort the radiation pattern and/or alter the antenna's terminal impedance slightly.

Bumper mount installations for low-band VHF, for example, may be selected based more on the antenna installation structural rigidity requirements than on ground plane symmetry, radiation pattern distortion, and other RF performance parameters.

Choices for hand-held radio antennas are, in practice, limited to short whip antennas. These antennas are physically very short, are typically inductively or resistively loaded (to simulate, electrically, a longer antenna and/or to provide a better impedance match). These features and attributes are accomplished at the cost of decreased antenna gain.

Selecting appropriate antennas for fixed stations is more critical than selecting the antennas for mobile and hand-held units. This is because antennas for fixed stations must be chosen to adequately receive signals from the least-capable mobile/hand-held units (those with low transmitter power, low antenna gain, low antenna height, *etc.*).

When designing a radio system for LMR use, a systematic development plan must be created and followed:

- Define System Requirements.
- Design System.
- Select Appropriate Components.
- Procure and Install Components.
- Perform Routine Maintenance.

Each of these steps is dependent on the previous step in the chain.

8.1 Define System Requirements

The design and deployment of an LMR communications system, or the upgrade or expansion of an existing system, generally begins with some knowledge of what geographic regions need to be "covered" by the radio communications system. This is a fundamental requirement that is determined by the nature of an agency's jurisdiction, where population and transportation routes are located, and so on. These requirements must be developed by the agency itself.

Several other system-level requirements can also be developed by the agency before obtaining the services of a radio system vendor or consultant. Larger law enforcement agencies will have a communications department that will perform these services. The number of mobile and handheld units, for example, is usually determined by the number of users that must be supported.

Next, some decisions must be made regarding how many channels will be needed. For example, one or more channels may be needed for dispatch functions. Additional channels may be needed for mobile-to-mobile communications. Other channels that might be needed could include:

- A local command channel for operations at an event site.
- A channel to interoperate with other agencies in mutual-aid situations.
- A channel dedicated to tactical forces.
- Other channels to support the operational and administrative activities of the agency.

Other aspects that may affect system design include:

- The typical length of messages for the various channels and talk groups.
- Maximum level of activity for the dispatch channel.
- The nature of operations that use the local command channel.
- Geographic coverage requirements.
- The specific level of performance (*i.e.*, speech intelligibility and/or data-transmission throughput) required.

Having a working knowledge of these system-level requirements will help ensure efficiency in the system design process that follows, and will help ensure the reliable performance of the system when it is fully deployed.

Begin by developing some initial system requirements. Consider, for example, the following:

- At what frequencies will you be transmitting? Lower frequencies require larger antennas. Higher frequencies have more limited range. A wide range of frequencies will require multiple antennas, multiband antennas, or broadband antennas.
- What is the maximum distance over which your users must communicate? Systems to support distant itinerant users will require a combination of higher-power transmitters and antennas with greater gain.
- What is your coverage area? Required antenna radiation patterns will be dictated by the location of the fixed site relative to the required coverage area.
- Are there other nearby radio systems operating in neighboring frequency bands or on the same or adjacent frequency channels? Your system might cause interference to these other users, or conversely, these systems might cause interference to your new system.
- What physical limits are there on your design? Is there sufficient property to construct a site, or is there sufficient space on shared antenna towers for your system? Will building code and zoning ordinances impact the construction of your system?

- What about standby/back-up systems at this site or at another antenna site?
- What level of speech intelligibility is required? How much noise and distortion can be tolerated? For data transmissions, what data-throughput rates are required (how large is the data file and how much time is available for transmission)?

8.2 Design System

The decisions that must be made during the design of a new system or the expansion of an existing system include:

- The number of base and repeater stations and their locations.
- Some initial choices of antennas and antenna heights for those fixed sites.

The design process will require the identification of:

- The availability of channels in the various LMR frequency bands.
- Potential/alternative base and repeater station locations.
- The potential for sharing fixed-station infrastructure among multiple agencies.
- The estimated cost of the system.

8.3 Select Appropriate Components

Once the system performance and system design requirements have been ascertained, the antenna characteristics that must be considered are the antenna system gain and radiation pattern. The process of identifying the needed gain and pattern is usually an iterative one. The process might proceed as follows:

First, coverage predictions are made. Values for transmitter power, operating frequency, antenna system losses, antenna gain, antenna height, antenna pattern, and minimum acceptable received signal strength for some specified level of speech intelligibility are required in order to make these coverage predictions.

Intermodulation interference analysis must also be considered during the design phase, particularly where multiple transmitters, receivers, and/or repeaters are collocated. Antenna system manufacturers and vendors can assist agencies in predicting the likelihood of IM interference or receiver desensitization, either caused by or inflicted upon the proposed new system. To mitigate IM interference at repeater and base station antenna sites, their designs will include isolators, cavity filters, duplexers, combiners, and multicouplers. The number of collocated systems and the frequency separations between them also influences the choice of combiner and duplexer components.

System design and component selection continue by interactively trying different antenna gains, patterns, and heights at each potential site location until the desired coverage is attained. Then, antenna system installation at each fixed site needs to be considered. Points to consider include:

- Antenna tower height—Will the proposed antenna tower conform to local building codes and zoning ordinances?
- Environmental considerations—Will the antenna system and supporting structure survive expected wind loading, ice loading, and other anticipated environmental

performance factors? EIA/TIA Standard 329-B [19], EIA/TIA Standard 329-B(1) [20], NIJ Standard-0204.02 [21], and NIJ Standard-0205.02 [22] all provide guidance regarding the minimum environmental, as well as RF, performance criteria required of all antennas used in the law enforcement and corrections arenas.

- Security—Is the site secure against unauthorized intrusions, yet accessible to maintenance personnel?
- Accessibility—Could inclement weather (*i.e.*, deep snow drifts, washed-out dirt access roads) prevent maintenance personnel from reaching the site?
- Co-site analysis and IM interference—Will retrofitting new systems into existing infrastructures introduce adjacent-channel interference, co-channel interference, IM interference, or receiver desensitization upon other existing systems or upon the new system? Will other nearby users and systems detrimentally affect the performance of the new system because of these problems? How will the vendor mitigate predicted interference problems? Does the vendor have a plan to mitigate unforeseen interference problems?
- Power source—Is commercial electrical power available? Will solar/battery power be required as primary/backup power?
- Wireline/wireless link—Is telephone service available? Is fiber optics service available? Will microwave radio be required?

9. INSTALLATION, MAINTENANCE, AND SAFETY

9.1 Vehicular Antenna Systems

The procurement and installation of vehicular antenna systems are relatively straightforward. If the design requirements have been well thought out and adequately described in the procurement documents, a competitive procurement will deliver an acceptable product.

When installing a vehicular antenna system, care must be given to routing the coaxial cable between the radio and antenna. The cable should not be exposed to the elements (wind, road salt and sand, rain, intense sunlight, extreme heat, *etc.*) nor should it be in a location where it could be severed or pinched (by opening and closing vehicle doors, for example) or where a vehicle's occupants might become entangled with it. One preferred routing for a roof-mounted antenna might be between the roof and interior headliner of the vehicle, down through a windshield pillar, and behind the dashboard panel to the radio. Other equipment, such as *duplexers* (to combine multiple radios operating in different frequency bands onto one multiband antenna), should likewise be installed in locations not readily accessible to vehicle occupants. For example, they should be installed under seats or in trunks where they are "out of the way," yet reasonably accessible to maintenance personnel.

RF cable connections should be torqued to the proper force recommended for the particular connectors used, and the outer grounded conductor of the antenna base mount must be RF-bonded to the metal of the roof or trunk deck. Trunk deck installations also require excellent RF bonding from the trunk lid to the main vehicle body. One way to accomplish this is by using a short length of low-impedance copper grounding strap affixed to bare areas of (interior) sheet metal on the underside of the trunk deck and the main vehicle body, using noncorrosive bolts, star washers, and lock nuts. A poor ground connection will detrimentally affect antenna operation, resulting in erratic or unacceptable performance.

9.2 Fixed-Site Antenna Systems

Most new installations of fixed-repeater and base-station antenna systems will likely be performed by contracted installers or equipment suppliers. In many cases, retrofitting new or upgraded components into existing facilities will similarly be performed by contracted installers or equipment suppliers. Procuring agencies should, nevertheless, ensure that the installer observes sound installation practices. As with vehicular grounding, proper ground protection of fixed station antenna facilities is important.

9.2.1 Fixed-Site Antenna System Grounding and Bonding Practices

An effective grounding system is necessary for every antenna tower. In addition to the protection a grounding system offers from lightning strikes, grounding also:

- Reduces the hazards of electrical shock resulting from ground/neutral power faults.
- Protects wiring and circuitry by limiting extraneous over-voltages.

- Facilitates rapid discharge of faulted power circuits.
- Reduces noise voltages.
- Provides a path to dissipate any stray RF current present inside the transmitter station; ungrounded RF currents can contribute to equipment malfunction, or create interference with other receivers.

9.2.2 Fixed-Station RF Bonding

RF bonding is another important aspect of fixed-station antenna systems. Simply connecting each element of a transmitter facility to a metal pipe stuck in the ground is barely adequate to act as a grounding system. The components of such a grounding system are not perfect conductors and each will have different, finite values for resistance. The resistance and physical design of the grounding system adds to the overall resistance and reactance of the antenna system and transmission line, causing the system to have different voltage potentials at different points within the system, inducing stray currents to flow between equipment chassis. These stray currents can affect internal circuits of the equipment and cause erratic operation and unpredictable behavior.

A bonding system ensures that all equipment grounding points are at the same electrical potential. A good dc and RF bonding system will use high-quality, low-impedance copper strap or braid and attach all equipment chassis to a low-impedance copper bus strap installed on the walls throughout the station facilities. The copper bus leaves the station and is attached to the Earth using a copper ground rod approximately 3 m long. The point of egress for the facility ground should be at the same entry point as RF cable, telephone, and power connections.

9.3 Lightning Protection

The National Fire Protection Association (NFPA) publishes a guideline related to lightning protection [23]. This guideline details many additional practices for protecting radio equipment from lightning strikes.

Metal antennas and towers should be connected to the building's lightning protection system. Wires and metallic elements comprising an antenna tower's lightning protection system should be electrically attached to the Earth. Towers and guy wires anchored to concrete forms in the ground are often assumed to be well grounded, but concrete is a poor electrical conductor. Tower legs should be electrically attached to the Earth with a copper ground stake approximately 3 m long. Lightning-ground connecting leads connecting the tower to the ground stake should be at least AWG #10 copper, AWG #8 aluminum, or 3/4 in copper braid.

The transmission lines must be protected by lightning arresters, protectors, and discharge units. Arresters can be placed at both ends of the transmission line for added protection.

9.4 During Installation

Be sure the installer knows exactly where on the vehicle or on the antenna tower the antenna components are to be installed. Make sure they are installed in the correct orientation and positioned correctly.

Make sure that the ends of the transmission line cable have been prepared properly before affixing RF connectors to the transmission line. Make sure that the RF connectors are properly installed on the transmission line. Loose connector assemblies will result in poor ground connections between the outer connector shell and the outer shield of the transmission line. Make sure that the center pin is securely affixed to the center conductor of the coaxial transmission line and that the center pin's depth, relative to the connector shell, is maintained at the correct distance, or an impedance mismatch or connector damage will result. Make sure that the antenna and transmission line connectors will mate properly before connection to other equipment is attempted. Connectors can be easily misaligned or over- or under-torqued, resulting in degraded or erratic overall RF performance. Make sure that the transmission line has not been damaged in any way, such as crushed, severed, or pinched.

Check the VSWR as soon as possible after installation, and, if possible, before the installer leaves the job site. In addition to VSWR measurements, time-domain reflectometry (TDR), line-fault measurements are helpful. Use a portable transmitting unit if the radio transmitter is not yet installed. Record the VSWR values and TDR data for future reference.

Measure and record the ambient noise power levels for future reference.

If possible, the installer should conduct "over-the-air" RF power sensitivity measurements immediately after installation, and document the test configuration and measurement results for future reference. For example, a portable antenna mast, 7 m to 10 m high, could be placed at a geological survey marker that has unobstructed, clear, visual line-of-sight to the repeater or base station-antenna tower. A portable transmitter could serve as the signal source. A similar method could be used to measure the power received by a portable radio service monitor (such as an IFR1500 or Motorola R-2670) located at the survey-marker point.

Make a physical inspection of the installation. Be sure all connectors and transmission lines are secured properly.

9.5 Perform Routine Maintenance

After a vehicular or repeater/base-station antenna system has been installed, the system will require periodic maintenance to ensure optimum performance.

Agencies should practice three tiers of maintenance. The first is performed by the radio operators and consists of simple, "common-sense" inspection of the equipment. The second level of maintenance is performed by site technicians and requires the use of land mobile radio test equipment. The third level of maintenance is performed by factory-authorized technicians.

9.5.1 Local Inspection

Radio operators themselves can perform a wide variety of simple aural and visual inspections of their radio equipment and antennas. For instance:

- Isolated problems noted with reception or transmission in the field. Direct comparison between two radios ("I cannot hear the base station when I am in this location." "Oh, really? I can hear the base station okay.") gives an excellent indication of a problem with a subscriber unit.

- Loose or missing connectors—Over time, temperature variations, shock, vibration, exposure to the elements, and handling can cause connections and connector flanges to become loose or missing altogether. Rubber O-ring grommet seals may deteriorate, allowing moisture to penetrate into connectors or the transmission line, altering their performance.
- Cracked or broken whip antenna base-loading coils—Cracks in the plastic housing of vehicular antenna base-loading coils can permit moisture and corrosive materials to penetrate into the loading coil, altering the antenna's electrical performance. Weathering of rubber grommet O-ring seals (where the loading coil is affixed to the roof or trunk deck of the vehicle) may similarly permit moisture and corrosive materials to penetrate into the connector between the loading coil and its attachment to the coaxial cable connector, altering the antenna's electrical performance.

9.5.2 Site Technician

The site technician will often have an array of RF test equipment at his or her disposal. For example, a communications service monitor can determine whether a radio is transmitting on the proper frequency, at the proper power level, with the proper frequency bandwidth. A VSWR meter gives an indication of how well RF energy is coupled from the radio system into the antenna. A time-domain reflectometer can determine where faults or other discontinuities exist along the length of a transmission line. Portable field strength meters can give an indication as to whether the antenna radiates electromagnetic energy as expected.

Vehicular antenna systems should be periodically checked according to an established maintenance schedule, typically concurrent with the maintenance schedule of the mobile radio (perhaps once or twice per year). Performance values such as VSWR should be recorded, compared to the performance values measured just after installation, and tracked over time in order to assist in keeping the antenna system functioning at an optimal performance level.

The above statements apply equally to fixed-site repeaters and base stations. Unfortunately, whereas problems with mobile and portable radio systems can be readily identified by direct performance comparison at the operator level, such is not necessarily the case for fixed sites. Because performance degradation at the fixed site affects all subscriber units equally, slowly occurring degradation in performance, caused by corrosion effects, weathering, *etc.*, may go unnoticed for years until catastrophic failure finally occurs. Therefore, regularly scheduled site visits to conduct maintenance performance inspections must be a part of the site technician's routine. Recording a time history of the RF performance, and comparing it to the RF performance measured immediately following the repeater or base-station installation, will be an invaluable maintenance aid.

Remote automated in-line diagnostic test equipment can also provide indications of needed maintenance. Several vendors of antenna system equipment, such as Bird Electronic Corp., Decibel Products, Sinclair Technologies, Telewave, and many others, manufacture remote in-line diagnostic measurement equipment. This equipment can report the health and status of a fixed repeater/base-station site's RF performance, up to the point where the radio wave is launched into space. For example, conditions of low transmitter power and/or excessive VSWR, which might result from detuned combiner cavities or duplexers, failing radios, weathering of components, *etc.*, can be sensed by the automated diagnostic equipment. Alarm conditions can automatically be reported to a computer by preconfigured telephone dial-up to the centralized maintenance facility.

9.5.3 Factory-Authorized Technicians

If an antenna system or radio problem is too complicated for the local site technician to repair, the manufacturer should be contacted. Many large public safety organizations have service contracts with factory-authorized repair facilities to maintain, repair, and replace equipment. Even without a contract, contacting the manufacturer about specific problems is advised if the problems are beyond the abilities of the agency to repair.

9.5.4 Antenna Tower Safety

Working on antenna towers can be dangerous and potentially fatal. Serious personal injury and equipment damage can result from personnel falling, improperly installed equipment, and RF radiation exposure.

When maintenance personnel must work on antenna towers, safety equipment should be selected, used, and cared for as if their lives depend on it—because they do! A list of safety equipment should include:

- Safety belt.
- Safety glasses.
- Work boots with firm, nonslip soles and well-defined heels.
- Hard hat.

It is recommended that antenna tower installations have a personnel fall-arrester system. These systems permit maintenance personnel to attach their safety belts at ground level, and remain attached during tower ascent and descent, as well as while working at height. Antenna tower manufacturers, such as Rohn Tower, offer fall arrester systems, which comply with OSHA regulations.

In addition to personnel safety while ascending, working on, or descending antenna towers, maintenance personnel must be cognizant to the danger of RF electrical burns arising from direct contact with energized antenna elements, and to exposure to high levels of RF radiation. Industry standards have been developed that specify the levels of electromagnetic exposure to which personnel can be "safely" exposed [24]. Personnel working on transmitting antenna towers *must ensure* that *all* antennas that they are working on or near are disconnected from their associated transmitters, and that the transmitters are routed into dummy loads (to prevent damage to the transmitter final amplifier in the event of inadvertent transmissions), or that some sort of fail-safe mechanism for disconnecting power to those transmitters has been engaged.

Lastly, maintenance personnel should be alert to weather conditions. It is ill-advised to work on an antenna tower during an electrical storm or in high winds. Remember—safety first!

9.5.5 Vehicular Antenna Systems

The same precautions regarding RF exposure on antenna towers should be observed when operating or performing maintenance on vehicular antenna systems. For example, personnel should not stand outside and next to their vehicle (where they do not have the benefit of RF shielding afforded by the vehicle's roof that they would have if they were inside the passenger compartment of the vehicle) while operating a 45 W (or greater) mobile radio transmitter, nor should they touch the antenna when transmitting.

9.5.6 The Importance of Maintaining Your Radio System

It must be stressed that regularly scheduled, periodic testing and preventive maintenance of the entire radio system is of paramount importance. Motor vehicles used by law enforcement and corrections, fire, emergency medical services, and other public-safety agencies are maintained by complying with strict maintenance schedules. Weapons are maintained by following regular preventive maintenance schedules of cleaning, lubrication, and inspection for worn or damaged parts. The same *must* hold true for all parts of a radio communications system—the lives of fire, emergency medical services, and law enforcement and corrections personnel may depend on it.

10. ANTENNA SYSTEM RESOURCES

This section describes some of the resources available to agencies to research information about and identify pertinent products, antenna systems and related components. There are many qualified and conscientious manufacturers and products available; only a few are cited herein in order to provide a sampling of what is available.

10.1 Internet Resources

As the World Wide Web (WWW *or* Web) has grown in recent years, many antenna manufacturers and suppliers have created Web pages devoted to their products.

Most Web-page authors will register their page with one or more of the major "search engines" on the Web. A search engine is a program that will use a search phrase provided by a user (usually a single word or simple phrase) to search hundreds of thousands of Web pages looking for occurrences of the phrase. The engine will then return a list of those Web pages that most closely match the search criteria (*i.e.*, those that contain the search phrase). A few search engines, such as Metacrawler (http://www.metacrawler.com) conduct searches by simultaneously querying more than one search engine.

10.2 Periodicals

Several periodicals are written for the land mobile radio industry. Most are free to "qualified" subscribers. These periodicals contain articles of technical interest related to land mobile radio, and advertisements for land mobile radio systems, components, and services. These periodicals publish, as special issues, buyers' guides on an annual or biannual basis. One such periodical that does this is *Mobile Radio Technology* (URL: http://mrtmag.com, telephone *1–913–341–1300*). Another is APCO's monthly *APCO Bulletin* (URL: http://www.apcointl.org/bulletin/, telephone *1–888–APCO–911*). Public libraries may maintain subscriptions to this and other LMR-related periodicals, or they may be able to obtain issues under interlibrary loan agreements.

10.3 Manufacturers' and Vendors' Catalogs

Most antenna manufacturers and vendors distribute free catalogs that describe antennas, transmission lines, and related components that they offer for sale. Most catalogs provide useful technical information such as antenna patterns, operating frequencies, physical dimensions, and costs. Frequently, these catalogs will provide basic explanations about various aspects of antenna systems, such as collocated transmitter-combining techniques, intermodulation interference, transmission line theory, *etc.*

Many manufacturers have more than one product line, *e.g.*, antennas and duplexers. Information about manufacturers' offerings can be identified and researched via the Internet or through the periodicals and buyers' guides discussed in the previous two subsections.