PUBLIC SAFETY

PSWN PROGRAM

WIRELESS NETWORK

Saving Lives and Property Through Improved Interoperability

In-Building/In-Tunnel User Considerations

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PREFACE

The PSWN Program is a jointly sponsored initiative of the Department of Justice and the Department of the Treasury. The program encourages interoperable communications among wireless networks to address local, state, federal, and tribal public safety requirements. It strives to achieve the vision it shares with the public safety community—seamless, coordinated, integrated public safety communications for the safe, effective, efficient protection of life and property. To support program goals and objectives, the program analyzes various aspects of wireless communications and provides findings, conclusions, recommendations, and other considerations from the respective analysis to the public safety community at large. This report details considerations for agencies requiring radio communications in confined spaces. Further detail regarding the PSWN Program and its products and services can be found at http://www.pswn.gov.

1. INTRODUCTION

1.1 Purpose of this Report

This report presents considerations for achieving adequate radio coverage in buildings and in tunnels especially since public safety agencies operate radios throughout a wide range of spectrum and each frequency has different characteristics. These considerations are provided to assist public safety agencies in meeting their unique needs for radio coverage in such confined spaces. It assembles a variety of information from the Public Safety Wireless Network (PSWN) Program's experience and the experience of system planners, manufacturers, and users in the field to help individual agencies assess their current coverage capabilities and their ability to remedy gaps in that coverage.

1.2 Coverage in Buildings and Tunnels

A radio system must be able to propagate or transmit a signal with enough strength to be received where needed. The system should have the capability to perform this function with a high degree of reliability under many different conditions. Engineers thoroughly understand free-space propagation, i.e., radio propagation between two unobstructed points in a vacuum, and can easily predict theoretical behavior. In a realistic setting, however, obstructions such as terrain, trees, buildings, and people, can affect signal propagation. These real-world obstructions can create difficulties in understanding and predicting radio coverage. The task becomes even more complex when trying to predict coverage in a confined space, such as within a building or inside a tunnel. Under these circumstances, coverage cannot be calculated to a certainty, only estimated.

Consider the following scenarios:

1) It is a warm summer afternoon in a metropolitan area when a 50-car freight train carrying hazardous chemicals derails spilling more than 5,000 gallons of hydrochloric acid into a downtown tunnel. The chemicals burst into flames and wreak havoc on the surrounding community, bursting pipes, disrupting public utilities, and causing black smoke to billow from holes in the pavement. First responders to the accident estimate the internal temperature of the tunnel to be in excess of 1,500 degrees. Limited access to the tunnel allows only a few fire personnel to enter the tunnel at a given time. Soon after leaving the safety and relative peaceful world above, the firefighters enter a hostile world of fire, debris, and other hazards where their communications to backup personnel or dispatch may be hampered.

2) It is a Friday afternoon as a police officer pulls up to a building. Just moments before, he received a radio call from a dispatcher informing him of a hostage situation developing on the ninth floor. Unknown to the officer, the perpetrators have secured the entire building, including the three-level parking structure beneath the tower. Initial intelligence reports indicate the building is being held by more than a dozen heavily armed suspects. The last thing on the officer's mind is whether he or she can communicate with his command center once inside the seized building.

The time to be thinking about your communication systems is *before* events such as these occur, not as they are developing. How does your communications network perform once you leave the relative safety of the "outside" world and enter buildings and tunnels?

1.3 Organization of the Report

The considerations outlined in this report are divided into two major components. Section 2, beginning on page 3, discusses propagation at a high level, describing expected radio frequency (RF) signal strength in various combinations of environments, antenna heights, and building materials. Section 3, beginning on page 11 discusses potential coverage solutions for the scenarios addressed in Section 2. For readers interested in the characteristics of radio propagation, a technical discussion of the physics behind confined space radio propagation is included in Appendix A. A glossary of the technical terms used in this document, with detailed definitions, is shown in Appendix B. The report concludes with Appendix C, which lists the references used while developing the In-Building/In-Tunnel User Considerations.

This report does not describe every possible communications challenge for confined environments. Instead, it provides information assembled from the PSWN Program's experience and the experience of system planners, manufacturers, and users in the field, which may assist the reader in solving the particular challenges they confront.

2. SIGNAL STRENGTH AND COVERAGE CONSIDERATIONS

This section presents general considerations for public safety agencies in understanding in-building and in-tunnel radio coverage in relationship to frequency and distance. Coverage is the radio system's ability to be heard by a receiver on the system and to have the receiving radio transmit back and be heard by the system. Generally speaking, radio coverage is best when the transmitter and receiver are within line of sight (LOS) of each other. The considerations presented in this section focus on identifying things that affect received signal strength considering different parameters such as area settings (i.e., urban, rural), building materials (i.e., glass, concrete), or variances in the transmitter-to-receiver distance. The tables in this section provide a qualitative coverage strength indicator for each public safety frequency band as it is affected by various situations and materials. Due to the nature of radio propagation and environments the signal may encounter, more than one of the obstructions or scenarios within each table may apply. For example, Table 2 shows that a 406–420 megahertz (MHz) signal has excellent penetration into low-density buildings. However, if foil insulation, concrete, or dry wall materials are used, the received signal strength within the building will decrease. In some cases, the received signal strength may decrease dramatically for each material encountered. Details supporting these considerations are discussed in later sections of this document.

Free-space propagation, or propagation with an unobstructed path between the transmitter and the receiver, is the mode to which all other modes are compared. Although theoretical in nature, free-space propagation provides a baseline to which radio propagation in the "real world" can be compared. Free-space propagation is considered theoretical because radio waves are transmitted in a vacuum, a condition that does not occur in the "real world." For "real world" radio propagation, physical obstructions (some as small as airborne particulates) cause signal loss. For a more in depth discussion on Free-space vs. "real world" propagation, please see Appendix A.

Obstructions include weather, terrain, and man-made obstructions. Heavy rain or snowfall, between the transmitter and receiver, may cause signal degradation due to absorption loss. The magnitude of this absorption loss depends on the frequency of the signal and the amount of rain or snowfall in the path. Further, mountainous or hilly terrain and foliage will cause shadowing, the partial blockage of the signal, and signal scattering generating even more attenuation. For more information on shadowing and scattering, please see Appendix B.

Man-made objects, like buildings or bridge overpasses, tend to affect radio signals in ways similar to mountainous terrain and foliage. These effects are presented in Table 1, in which signal strength is indicated in a range from "very good coverage" to "poor coverage." A rating of "very little coverage" or "poor coverage" is generally inadequate for public safety communications. As an example, mountainous terrain causes an area to receive "average" signal coverage, a rating that is much less than the "very good" coverage rating associated with free-space propagation. Obstructions, such as buildings, will cause radio signal strength degradation similar to, but generally more dramatic than that caused by terrain obstructions.

Assuming constant transmit power, radio coverage is typically greater (i.e., offers increased signal strength, and a greater coverage area) in a less dense environment, such as a rural area, compared with a dense environment, such as a metropolitan area. Coverage in a building is affected by the presence of obstructions within the path between the transmitter and receiver, including surrounding buildings, terrain, foliage, and the materials from which the building is constructed. Table 2 illustrates that, when holding constant all the other transmission parameters, lesser coverage (i.e., lesser signal strength and lesser coverage area) is generated in an urban area compared with a rural environment.

Table 1
Propagation with Natural Obstruction for Public Safety Frequencies

Public Safety Frequency Bands (MHz)	Natural Obstructions					
	Free Space	Atmospheric Loss 0 to 600 ft	Atmospheric Loss 600 to 1,200 ft	Weather	Mountainous Terrain	Foliage
25–50	4	4	3	4	2	4
138–144	4	4	3	3	2	3
148–174	4	4	3	3	2	3
220–222	4	4	3	3	2	3
406–420	4	4	3	3	1	3
450–470	4	4	3	3	1	3
764–776	4	3	2	2	1	2
794–806	4	3	2	2	1	2
806–824	4	3	2	2	1	2
851–869	4	3	2	2	1	2

4 = very good coverage 1 = very little coverage
3 = good coverage 0 = poor coverage
2 = average coverage

2.1 In-Building RF Coverage Considerations

Radio propagation in a building is much more complicated than propagation in free space. A number of factors affect radio coverage in a building. The building's relative location within an agency's coverage footprint may determine a major part of the building's internal communications capabilities. The building's size, layout and the materials with which the building is constructed also contribute heavily to the communications dilemma of in-building radio coverage. In-building communications can be defined in two possible ways—

- Internal unit-to-unit—or the ability of subscriber units to communicate with each other within the confines of the building
- Subscriber unit-to-external infrastructure—or the ability of a radio unit to communicate with infrastructure located outside of the building.

2.2.1 Building Materials

When propagating into buildings, radio signals pass through various materials before reaching a receiver's antenna. The interaction of these radio signals with building materials usually results in lower signal strength. However, it should be noted that signals behave differently when encountering an obstructing medium, depending on that medium's characteristics and specific electrical properties.[1] These electrical properties, which are unique for every material, dictate the extent to which a signal can transmit through the medium. More specifically, RF energy entering a building will be partially absorbed and partially reflected by the building materials encountered. To illustrate this concept, a signal traveling through a simple glass window will lose less signal strength than a similar signal traveling through a glass window containing high concentrations of lead or other metals. In a very similar scenario, a signal will propagate through concrete more readily than through concrete with steel re-bar. These effects are presented in Table 2.

Shown in Table 2 is a summary of how radio signals perform in different building environments. This table is based on conclusions drawn from research, industry experience, and laboratory modeling. The figures are intended to provide a qualitative indication how these frequency bands perform under the identified environments. Signal strength is indicated in a range from "very good coverage" to "poor coverage."

2.2.2 Receiver Heights Within a Building

Depending on the location of the receiver relative to the transmitter, signal strength will vary due to obstructions, weather, separation distance, and reflections. It is not always practical to maintain or establish a LOS, however, receiver height may increase the ability to communicate.

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[1] The electrical properties that affect in-building and in-tunnel radio coverage are permittivity, permeability, conductivity, and susceptibility. For further explanation of these properties, please see Appendix B—Glossary of Terms.

Further, the receiver location within a given building with respect to the transmitter is also a prime factor. A radio user trying to receive signals on the first floor of a building (from outside the building or from different points within the building), in an environment with other surrounding buildings, will more likely not have a clear LOS. Received signals on the first floor may be blocked due to shadowing caused by the neighboring buildings and/or foliage. If a receiver was placed on a higher story, the user might have a better chance of receiving the signal. This improved signal would likely be a result of rooftop diffraction off nearby buildings, a higher probability that the receiver is above the foliage, or even newly established LOS.

Below ground level, such as in basements or underground parking structures, radio users generally experience lower signal strengths than levels above grade. This degradation occurs because the signal must propagate through earth in addition to building materials to reach the receiver, thus creating a large signal loss. The strength of a signal received in the basement is significantly less than that of a signal received on higher floors within the building. These effects are presented in Table 2.

Table 2
In-Building Radio Propagation Considerations for Public Safety Frequencies

Public Safety Frequency Bands (MHz)	Environment Setting			Receiver Heights Within a Building				Building Materials[2]								
	Rural Setting (low dense area)	Suburban Setting (medium dense area)	Urban Setting (high dense area)	0 to 30 ft below ground	0 to 50 ft above ground	50 to 100 ft above ground	100 to 150 ft above ground	Low Density Buildings	Medium Density Buildings	High Density Buildings	Plain Glass	Leaded Glass	Foil Insulation	Concrete	Metal	Sheetrock
25–50	4	3	3	1	4	4	4	4	3	2	4	4	3	2	1	3
138–144	4	3	3	1	4	4	4	4	3	2	4	4	3	2	1	3
148–174	4	3	3	1	4	4	4	4	3	2	4	4	3	2	1	3
220–222	4	3	2	1	4	4	4	4	3	2	3	3	3	2	1	3
406–420	3	2	2	1	3	3	4	4	3	2	3	3	2	2	1	2
450–470	3	2	2	1	3	3	4	4	3	2	3	2	2	2	1	2
764–776	2	1	1	0	2	2	3	3	2	1	2	1	1	1	0	1
794–806	2	1	1	0	2	2	3	3	2	1	2	1	1	1	0	1
806–824	2	1	1	0	2	2	3	3	2	1	2	1	1	1	0	1
851–869	2	1	0	0	2	2	3	3	2	1	2	1	1	1	0	1

4 = very good coverage
3 = good coverage
2 = average coverage
1 = very little coverage
0 = poor coverage

2.2 In-Tunnel RF Coverage Considerations

It is difficult to provide reliable radio coverage within a tunnel environment. One of the main reasons is the complex propagation environment of such enclosed structures. Every tunnel has unique propagation characteristics because of its construction, structure, and size. Presented in Table 3 is a summary of relative RF signal strength (i.e., coverage) in various tunnel environments. The information provided in Table 3 is based on conclusions drawn from research, industry experience, and laboratory modeling, as well as field testing using portable

[2] *For additional information on these building materials and their effect on radio communications, please see Appendix A.*

radios and various radio test equipment (e.g., spectrum analyzers and field strength meters) deployed in a Washington, DC, Metrorail tunnel. The study found that signals propagated better within the 800 MHz band compared to propagation within the very high frequency (VHF) and ultra high frequency (UHF) bands for a confined tunnel environment. This phenomenon may be attributed to the wavelength of each frequency band. As the wavelength decreases in size, or the frequency increases, it is more prone to be reflected within the environment. Rather than being reflected, the lower frequency signals tend to be absorbed by the tunnel walls more readily than the higher frequency signals. So generally speaking, higher frequency signals propagate better in tunnel environments.

This finding is supported by other studies conducted in various venues. One such study was conducted by independent researchers exploring wave propagation in curved tunnels to present to the Institute for Electronics and Electrical Engineers (IEEE). The tunnels used to study the wave propagation were located in Norway. In these studies a 925 MHz signal was transmitted in relatively straight tunnels approximately 10 x 5 m and 4 km long. The tunnels used in this study were constructed of materials (stone and rock) with average permittivity. In this study, it was determined that the average attenuation of a 925 MHz radio signal, transmitted at an effective isotropic radiated power (EIRP)[3] of 45 dBm was approximately 15 db/km. The findings of this particular study further verify the conclusion that higher frequency radio waves propagate better than UHF and VHF in tunnels.

Another study was conducted by the United States Bureau of Reclamation, Hydroelectric Research and Technical Service Group, in tunnels near Ephrata, Washington and Chama, New Mexico. In this study, analysts measured the differences between the performance of 160 MHz, 400 MHz, and 900 MHz handheld units in a tunnel environment. Further, 600 MHz and 1600 MHz signals were measured in the same tunnels to calculate signal strength versus distance. In these tests, the higher frequency (i.e., 900MHz) handheld units significantly outperformed the lower frequency handheld units, once again supporting the conclusions drawn from the previous two examples – that higher frequency solutions are generally more suited for in-tunnel applications.

It is important to note that like in-building communications, in-tunnel communications can cover either unit-to-unit conversations within the tunnel, or unit-to-external conversations. Due to the nature of tunnels, unit-to-external infrastructure communications can be quite challenging. Often external infrastructure does not provide adequate coverage into a tunnel for public safety communications and an alternative means of connecting in-tunnel responders to the external infrastructure may be necessary.

2.2.1 Tunnel Materials

RF energy leaving the transmitter antenna is partially absorbed and partially reflected by the tunnel material as the signal propagates down the tunnel. As shown in Table 3, due to the electrical properties of the tunnel materials, a signal may propagate more efficiently in a tunnel

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[3] *The EIRP of a transmitter is the power that the transmitter appears to have if the transmitter was an isotropic radiator, i.e., if it radiated equally in all directions. By virtue of the gain of a radio antenna, a beam is formed that preferentially transmits energy in one direction. EIRP is the product of the power supplied to an antenna and its gain.*

constructed of metal than a similar tunnel constructed with reinforced concrete. For example the metal tunnel will reflect more energy than it will absorb. A concrete tunnel, however, will absorb more energy than it will reflect; decreasing the distance the signal can propagate down the tunnel.

Table 3 summarizes how radio signals perform in tunnel environments. Signal strength is indicated in a range from "very good coverage" to "poor coverage."

2.2.2 Straight Tunnel

In a straight tunnel, the data indicated that 800 MHz signals travel significantly farther than VHF or UHF signals. The 800 MHz signal was acceptable throughout the entire measured 1,600 feet of the straight tunnel. According to the data, VHF coverage reached approximately 900 feet before the audio signal was severely degraded, as indicated by "poor coverage" in Table 3. UHF signals faded, as shown as a "very little coverage" indicator in Table 3, at approximately 900 feet and were severely degraded at 1,200 feet.

2.2.3 Curved Tunnel

RF signals propagating through curved tunnels experience a dramatic decrease in signal performance compared with that in straight tunnels. VHF and UHF signals faded at approximately 400 feet and 500 feet, respectively, in a curved tunnel. The 800 MHz signals traveled more than twice the distance of the VHF or UHF signals. For a curved tunnel, or non-line-of-sight path to the receiver unit, the RF signal received was limited to only that signal reflected beyond the curvature of the tunnel; thus, rendering a lower signal strength than one might expect from a LOS transmission.

Table 3
In-Tunnel Radio Propagation Considerations for Public Safety Frequencies[4]

Public Safety Frequency Bands (MHz)	Straight Tunnel					Curved Tunnel			Construction Material	
	0 to 300 ft	300 to 600 ft	600 to 900 ft	900 to 1,200 ft	1,200 to 1,500 ft	0 to 300 ft	300 to 600 ft	600 to 900 ft	Concrete	All Metal
25–50	4	2	0	0	0	4	2	0	2	3
138–144	4	2	1	0	0	4	2	0	2	3
148–174	4	2	1	0	0	4	2	0	2	3
220–222	4	2	1	0	0	4	2	0	2	3
406–420	4	3	2	1	0	4	1	1	2	3
450–470	4	3	2	1	0	4	1	1	2	3
764–776	4	4	3	2	1	4	3	2	2	4
794–806	4	4	3	2	1	4	3	2	2	4
806–824	4	4	3	2	1	4	3	2	2	4
851–869	4	4	3	2	1	4	3	2	2	4

4 = very good coverage
3 = good coverage
2 = average coverage
1 = very little coverage
0 = poor coverage

[4] The information provided in Table 3 is based on conclusions drawn from research, industry experience, and laboratory modeling, as well as field testing using portable radios and various radio test equipment (e.g., spectrum analyzers and field strength meters) deployed in a Washington, DC, Metrorail tunnel.

3. SOLUTION CONSIDERATIONS

This section presents options to assist public safety agencies in providing in-building and in-tunnel radio coverage. The following pages provide sample solutions that address a variety of constraints. The choice for the solution implemented can be influenced by RF interference effects on associated systems, and budget resources. The solutions presented in this section are divided into three categories based on the respective technology of the solution: simple, complex, and forward-looking. Further, where possible, approximate costs have been included in the summary tables to give the reader a rough estimate of cost impacts. For example, the first solution, a messenger, has been categorized as a technologically simple solution that has minimal cost.

This section describes individual solutions; however, a combination of solutions may serve an agency better than any single solution. For example, to achieve adequate in-building coverage for an emergency response at a high-rise building, an emergency operations plan may call for the use of an audio switch, mobile command post, and portable repeater, in addition to a backup plan of messengers. Other combinations of solutions could support mission requirements for ad hoc emergency response as well as for fixed, known coverage trouble spots. For example, an agency may wish to develop a portable audio switch solution in conjunction with a bi-directional amplifier network that is installed in the downtown district of the city.

It is important to note, however, that if agencies using disparate systems have already developed an interoperability solution for use outside buildings and tunnels, then they may only need to implement a similar interoperability solution inside the buildings and tunnels. Interoperability outside of buildings and tunnels does not always translate into in-building or in-tunnel interoperability. For example, if each agency uses a switch based system for interoperability, then a similar switch solution for in-building or in-tunnel interoperability may be required.

3.1 Technologically Simple Solutions

This section addresses the technologically simple solutions summarized in Table 4. These solutions are generally the most basic options an agency can implement. For the purposes of this document, technologically simple solutions are those solutions that do not require any specialized training or skills to implement and understand.

3.1.1 Messenger

In 490 BC, a military commander dispatched an unknown runner to Athens to inform the council that the Persians had been defeated on the plains of Marathon. Since the advent of land mobile radio (LMR) and other wireless devices, the need to dispatch messengers has been all but eliminated. However, when communications fail or are simply unavailable, dispatching messenger personnel to relay information from the responders to the incident commanders is sometimes the only means of transferring information. Dispatching a messenger does not require an installation or establishing common frequency bands that other solutions may require. While this solution may provide benefits, it assumes personnel are available to relay messages, and is not practical over an extended period of time. Furthermore, information integrity may be put at greater risk as the number of personnel increases from the point of origin to the destination.

3.1.2 Talk-around or Simplex

Although the messenger solution may be the least costly option, the talk-around or simplex option is a close second. Because it is highly portable, users may be able to employ this solution in the confined environments of buildings and tunnels. This solution requires both parties to possess radios that operate with the same technology, in the same frequency band, and that have a simplex or talk-around capability. As long as each radio is within coverage range of the other radios being used, this solution can be employed in just about every environment. For example, responders operating within a confined space and are within range of other portable or mobile radios can use the simplex feature of their radio to communicate with each other. Further, this solution may be used in a user relay format, much like the game of telephone, to reach the external infrastructure. This solution is limited by available power output of the radio and by the electrical properties of the confined space.

3.1.3 Portable Repeater

When the situation requires a more robust solution, the talk-around or simplex option is generally too limited to provide the needed services. Portable repeaters, however, afford the luxury of a more *powerful* system without the complex installation of a *larger* system. Also, the nature of a portable repeater enables an organization to install it for use in a temporary assignment. For instance, an executive protection detail can deploy a series of portable repeaters for temporary communications as the person the detail is protecting moves from location to location. While this solution may sound ideal, it too has its drawbacks. Both in-building and in-tunnel scenarios could call for implementation of this solution depending on the requirements of the response units. If the repeater is confined to a large case or vehicle it may not be feasible to use the unit in some situations such as in a collapsed tunnel or sub-basement.

Portable repeaters were designed to provide ad hoc coverage in areas where existing LMR infrastructure does not exist to radio users operating on the frequency for which the portable repeater is licensed. These repeaters can be used in conventional and trunked systems and are mostly limited by the interference they may cause with existing systems (e.g., local public safety or commercial networks) in the area. In some instances, portable repeaters may be used to extend the coverage area of an agency or provide a semi-permanent solution until a more permanent solution becomes available. Other shortcomings include limitations tied to available portable power supplies and insufficient capacity.

3.1.4 Bi-Directional Amplifier

The bi-directional amplifier (BDA) is perhaps one of the most common solutions to the in-building or in-tunnel dilemma. Originally designed to provide supplemental radio coverage in difficult coverage environments, the bi-directional amplifier has become a valuable tool in providing agencies with an in-building or in-tunnel projection of their radio network. A BDA system consists of one or more amplifiers located inside a confined environment and is connected to an internal and external antenna network. The external antenna, usually located on the roof of the building, or mouth of the tunnel, needing coverage, receives the signal coming from the radio site. The BDA amplifies the signal and retransmits it into the building or tunnel. A subscriber unit within the building can use the BDA to extend his portable radio coverage and communicate with his external system. The BDA listens for incoming traffic inside the confined space, amplifies it and retransmits it to the external system, hence bi-directional. A BDA can be relatively inexpensive. However, it is the supporting infrastructure of cabling, antennas, filters and power supplies that puts this solution in the medium cost category. Furthermore, unless BDAs are adjusted correctly, they can create interference issues—with themselves, through negative feedback; with other BDAs; or with the agency's existing radio system.

3.1.5 Radiating Coaxial Cable

Radiating coaxial cable, also referred to as leaky coax, is installed in subway tunnels, ships, and buildings around the world. The low profile nature of this solution makes leaky coax attractive for building and tunnel applications. It can be used where a BDA is impractical or unsuitable, such as in subway tunnels where a low-profile antenna is required to avoid physical interference with passing passenger trains. The design of the radiating coaxial cable provides uniform coverage throughout the tunnel (where installed). In addition, radiating coaxial cable has provided coverage benefits for a wide band of frequencies. It is important, however, to note that radiating coaxial cables are not perfect solutions for every environment. Radiating coaxial cables are passive devices. They can be used in conjunction with BDAs or repeater systems to increase a systems in-building or in-tunnel coverage. Leaky coax is highly susceptible to electromagnetic interference in high electromagnetic environments such as rail tunnels used in conjunction with diesel locomotives. The electromagnetic fields created by the locomotive's generators can easily overwhelm a leaky coax solution.

3.1.6 Vehicular Repeater

A vehicular repeater is a component used in conjunction with a mobile radio, which effectively expands the range of a portable radio in the field. To illustrate this concept, as an officer leaves his/her vehicle and begins transmitting on his/her portable radio, the 3-5 W portable radio signal is boosted through the vehicular repeater, thus enabling transmission at much greater distances and the enhanced ability to penetrate in-building or in-tunnel. For in-building or in-tunnel scenarios, the vehicular repeater can be brought to the scene to improve the localized communications in the emergency response area. The vehicular repeater typically is not limited by a power source and is highly mobile. However, a disadvantage can be limited versatility in confined or remote environments.

Table 4
Technologically Simple Solutions

Solution(s)	Advantages	Disadvantages	In-Building or In-Tunnel Solution	Approximate Cost	Examples of Use
Human Runner	• Not dependent on available spectrum • Has a lower cost than implementing a physical solution • Can be used as a temporary solution • Is the simplest solution	• Requires dedicating human resources to the task • Can result in a possible loss of message integrity • Is not practical as a permanent solution	Both	Human resource, material cost minimal	Any situation where wireless communications have failed or are not available
Talk-around or Simplex	• Is portable • Can operate within any environment • Is usable by most radios	• Has limited versatility in confined environments • Is limited by power supplies • Requires radios to be within coverage of each other • Requires mutual aid frequencies between radios	Both	Talk-around or simplex available in existing radios	Used by personnel to establish communications when access to a repeater is not available or desired
Portable Repeater	• Is portable • Has a flexible installation • Is a temporary solution	• Can be difficult to find antenna mountings • Requires power source • Provides a single channel with limited capacity • Is limited by logistical concerns such as who receives these radios, or how other radios can be integrated into the system	Both	<$25,000	Used by security organizations to establish temporary communications, used in public safety events to increase communication capabilities, such as county fairs, or festivals.

Solution(s)	Advantages	Disadvantages	In-Building or In-Tunnel Solution	Approximate Cost	Examples of Use
Bi-Directional Amplifier (BDA)	• Can be used with directional antennas to provide improved coverage	• May cause interference with existing system • Must be adjusted to prevent destructive interference from feedback or other BDAs	Both	>$20,000	Commonly used in buildings and tunnels to boost the coverage
Radiating Coaxial Cable	• Propagates uniformly • Has a low profile • Can be installed where omni-directional or directional antennas are not suitable	• Has poor performance in high electromagnetic environments • Susceptible to interference	Both	$3-$7/foot + installation hardware	Used within tunnels, ships, and buildings where it may not be feasible to use BDAs with directional antennas
Vehicular Repeater	• Is mobile • Transmits at a higher power than portable radios • Is not usually limited by power supplies • Can boost the radio coverage in the crisis area	• Has limited versatility in confined environments • May not provide adequate in-building coverage because of low RF penetration • Limited selection of hardware vendors	In-building primarily, in-tunnel where possible	$4,000 to $100,000	Used to amplify the signal from a portable radio

3.2 Technologically Complex Solutions

This section presents the in-building/in-tunnel solutions that are technologically more complex than the solutions presented in the previous section. For the purposes of this document, technologically complex solutions are those solutions that require specialized training or skills to implement and understand. These solutions are summarized in Table 5.

3.2.1 Audio Switch

An audio switch is a device generally used in public safety to connect radio systems. In most cases, a radio from one agency is connected to the switch. The switch patches the audio signal from the first radio through to another radio. Then the other radio retransmits the patched audio on its own system. Audio switches can vary in complexity from patching audio to a single radio, to very complex switches capable of connecting several radios, phone lines, satellite and cell phones together. Advanced features as specialized call tones and encryption may not be available with some switches.

Similar to a portable repeater an audio switch can be inserted into a confined space to act as a relay between users inside the building or tunnel as well as between users inside and external to the building or tunnel. Like the portable repeater option, this solution can be as portable as its installation allows.

In addition to potentially providing extended radio coverage for a system's users, the audio switch has become a staple in interoperability solutions by providing a means of connecting disparate radios together to achieve interoperability. Unlike the repeater option, the audio switch can be used to interface multiple users regardless of the frequency band on which their systems operate.

This solution is limited by the capacity of the switch—the number of units it can service. Depending on the size of the crisis area, several units may be required to cover the operational envelope. Furthermore, the unit depends heavily on a steady power supply to maintain connectivity. And finally, this solution generally requires software programming for each additional radio added to the switch.

3.2.2 Fiber Optic Transmission Line

While leaky coax is ideal for some tunnel applications, it is not always the best choice, especially when considering environments that have high level of electromagnetic interference (EMI) (e.g., train tunnels used with diesel engines). In such environments, one option to consider is a RF transport medium not susceptible to EMI, such as fiber optic cable. This solution, however, is best used in conjunction with other in-building or in-tunnel solutions such as BDAs. In order to use a fiber optic transmission line, additional equipment is required to translate the radio signal into digital light pulses for transmission on the fiber optic line. Thus rendering fiber optic cables a point-to-point technology. Fiber optic lines can be used in a multiplexing environment. Multiplexing is sending multiple signals or streams of information on a carrier at the same time in the form of a single, complex signal and then recovering the separate signals at the receiving end. Digital signals are commonly multiplexed using time-division multiplexing, in which the multiple signals are carried over the same channel in alternating time slots. In some optical fiber networks, multiple signals are carried together as separate wavelengths of light in a multiplexed signal using dense wavelength division multiplexing.

Like leaky coax, fiber optic lines have a low installation profile to avoid physical interference with their environment. The installation and supporting hardware required to use fiber optic transmission lines, however, is generally more expensive than a typical leaky coaxial cable or other transmission line. Cost drivers for fiber optic cabling are that they are components of digital systems and require converters at each end of the transmission line.

Table 5
Technologically Complex Solutions

Solution(s)	Advantages	Disadvantages	In-Building or In-Tunnel Solution	Approximate Cost	Examples of Use
Audio Switch	• Can interface with multiple users • Is portable • Extends existing infrastructure	• Is limited by the number of users it can service • Requires a power source • May require several units depending on the size of the building or tunnel, and the operational envelope • May require programming for each radio added to the system	Both	$5,000 to $60,000	Used by emergency personnel assisting with the rescue and recovery operation after the Pentagon attack
Fiber Optic Transmission Line	• Is not affected by high electromagnetic environments • Has a low profile • Allows signal multiplexing	• Must be used in conjunction with a transmitter/receiver and optical-to-electrical converter • Requires installation • Is more expensive than radiating coaxial cable • Requires analog-to-digital converter for use with analog systems	In-tunnels	>$20,000	Used by railroads within tunnels because of high electromagnetic environment created by the locomotives. Also used in hazardous materials environments where radio frequency energy can be dangerous

3.3 Technologically Forward-Looking Solutions

This section addresses the solutions that are technologically forward looking. For the purposes of this document, technologically forward-looking solutions are those solutions that take into consideration the prospect of newer technologies. Generally these solutions will make the transition to future technologies less cumbersome. These solutions summarized in Table 6.

3.3.1 Ordinances for New Construction

An ordinance for improved public safety communications in new building construction is an option that many municipalities are beginning to implement. The purpose of an ordinance is to mandate radio-friendly infrastructure inside new construction. The major advantage is that the radio coverage is designed into the structure from the start. Although not directly associated with the cost of a system, this solution is included to identify another means of ensuring adequate in-building or in-tunnel coverage when implementing new systems that are otherwise inherently costly.

3.3.2 System Level Requirements

As system planners address the next-generation communications network, in-building or in-tunnel radio coverage should be viewed as a system requirement. In addition, the system can be designed to cover known coverage “trouble spots” within buildings and tunnels. These benefits, however, do not come without a cost. More stringent requirements for building and tunnel coverage generally increase the number of radio sites a designer uses, and thus significantly increase the total cost of the project. Replacing a recently implemented system with a newer system generally is not feasible. However, system planners should include building and tunnel coverage criteria into future procurements. The City of Mesa, Arizona, for example, insisted on providing a minimum level of in-building coverage with its new system. For coverage “trouble spots,” the city allocated additional funding to address those areas with a lower cost solution such as a BDA.

3.3.3 Hybrid System Using BDA and Fiber Optics

Using a hybrid system of BDAs and fiber optic transmission lines combines the advantages gained by utilizing a high bandwidth medium, not susceptible to EMI, with the functionality of the BDA. As stated, an ideal use for this solution is in a railroad tunnel in which there is a high level of EMI. Another environment in which this option makes an excellent solution is in hazardous material environments in which the transmission of RF energy can be dangerous.

Table 6
Technologically Forward-Looking Solutions

Solution(s)	Advantages	Disadvantages	In-Building or In-Tunnel Solution	Approximate Costs	Examples of Use
City Ordinances for New Buildings to Provide Access to Public Safety Communications Network	• Establishes a vehicle for improved coverage in future construction • Can be a low-cost solution if the city is interoperable	• Does not address older structures • Requires legislative changes to city code	In-building	Costs of materials and construction are dependent on the Ordinance	City of Burbank, CA, has passed legislation requiring new structures to provide radio coverage for public safety agencies
New System Designed Explicitly to Include Coverage in Buildings and Tunnels	• Can be designed to meet the in-building or in-tunnel requirements of the agency • Can minimize interference issues • Can be designed to cover multiple buildings and tunnels if the need arises	• Has a very high cost • Must consider the life cycle of current system and make arrangements to include in-building or in-tunnel coverage in new system(s) • Can be difficult to specify adequate coverage for buildings and tunnels, including room for expansion	Both	> $1,000,000	City of Mesa, AZ, designed its system with in-building coverage in mind and allocated additional funding for "problem spots"
Hybrid System Using BDAs and Fiber Optics	• Combines the functionality of the BDA with the electromagnetic benefits of the fiber optics—ideal in environments where radio propagation will cause some concern or will be effectively neutralized by the environment	• Is more expensive than traditional BDA systems	Primarily in tunnels	>$40,000	Used by railroads within tunnels because of high electromagnetic environment created by locomotives

APPENDIX A—PHYSICS OF PROPAGATION

APPENDIX A—PHYSICS OF PROPAGATION

This section presents a discussion of the physics of radio wave propagation that must be considered when planning for in-building and in-tunnel radio coverage. A glossary of terms is provided in Appendix B to further explain the technical details of this discussion.

A.1 Radio Frequency Propagation in Free Space

When radio signals propagate in an environment free of obstructions (i.e., free space), one can predict their behavior by subtracting radio signal losses from gains. Gains enhance or increase signal strength while losses attenuate or reduce that strength. The results from summing the gains minus losses define the effective strength of the signal, and ultimately, whether the signal is strong enough for a receiver to recognize. To determine radio propagation in free space, the following factors must be considered:

- **Gains**
  - **Antenna Gain**—The gain of an antenna is the ratio of its radiation intensity to that of an ideal isotropic antenna (i.e., a hypothetical perfect antenna that radiates equally in all directions).
  - **Receiver Sensitivity**—The magnitude of the received signal necessary to produce objective bit error rate or channel noise performance.
  - **Transmit Power**—For the purposes of this document, transmit power will be defined as the power transmitted from the antenna, also known as the effective radiated power (ERP).
- **Losses**
  - **Atmospheric Attenuation Effects**—The atmosphere offers resistance to radio signals and lowers their strength. Changing atmospheric conditions, such as heavy rain or temperature fluctuations, can affect signal propagation. The effect atmospheric conditions can have on a signal can depend on the signal's wavelength. Generally, the higher the frequency, the more a signal is attenuated due to atmospheric absorption loss.
  - **Path Loss Due to the Separation Distance**—Electromagnetic waves radiate in all directions. Ideally (i.e., in free space) the signal will propagate from the transmitter without obstructions that might cause the signal strength to weaken. However, the signal will lose power as the distance it travels increases. Due to the Law of Conservation of Energy, as waves travel outward from an emitting source, the occupied area increases, but because energy is conserved, the energy per unit area must decrease. A signal strength loss of approximately 6 dB occurs as the distance doubles between the source and the receiver.

A.2 Radio Frequency Propagation in a World with Obstructions

In theoretical "free space," one can determine radio signal strength through simple calculations. Radio propagation in the "real world," however, is significantly different from theoretical free space. Many real-world factors hamper radio propagation. These factors include, but are not limited to, atmospheric absorption, multipath fading, signal power loss due to terrain obstructions, and signal power losses due to manmade obstacles. Generally, the more obstacles a wave encounters, the weaker the signal will be when it reaches the receiver.

Manmade obstructions, such as buildings and bridges, make much more abrupt changes than natural obstacles such as hills and trees. Because of these abrupt changes, more shadow (see Appendix B for more information on shadowing) loss occurs in and around buildings, reducing the signal strength in the region behind the obstacle.

A.2.1 Multipath Fading

An important factor to consider is multipath fading. In practice, transmitters and receivers are surrounded by objects. These objects constantly reflect and scatter the transmitted signal, causing several waves to arrive at the receiver at different times via different routes. As the signal is refracted and reflected off of various obstacles the power received at any given point varies. As a radio moves from point to point, the signal strength varies due to multipath fading. Depending on the frequency, a user may or may not notice the effects of multipath fading. Lower frequency signals have a longer wavelength (a 100 MHz signal has a wavelength of approximately 9.25 feet, whereas a 800 MHz signal has a wavelength of 1.25 feet) and would require the user to travel a greater distance to notice a discernable difference. Furthermore, the higher frequency signals generally reflect and refract more than the lower frequency signals (another function of a shorter wavelength), which may result in additional transmission paths. This phenomenon has been observed as an individual walks through a building with a portable radio and observes the signal strength fluctuating from point to point.

A.2.2 Material Characteristics

Each material has its own unique electrical properties, and each material will affect a signal differently. A signal's electric and magnetic field strengths diminish as the wave travels through a medium. As a signal passes through a material, some of the energy is absorbed and converted to heat. This is referred to as absorption loss. To further clarify, consider the theory associated with absorption loss and a practical example of this loss. Theory states the magnitude of these losses depends on the material's thickness and electrical properties. As evidence, a signal that passes through a thin wall will have stronger field strength after traveling through the medium than a signal that passes through a thicker wall of the same material and construction. Table A-1 lists the average signal loss for radio paths obstructed by common building materials. This table is intended to give relative losses per unit thickness for each of the materials listed.

Table A-1
Average Signal Loss for Radio Paths Obstructed by Common Building Materials

Material Type	Loss (decibels)
Wall constructed of metal plate	26
Aluminum siding	20.4
Foil insulation	3.9
2.7' x 2.7' square reinforced concrete pillar	12–14
Concrete block wall	13
Sheetrock (3/8 in)—2 sheets	2

A.3 Radio Frequency Propagation in a Confined Space

The previous sections discussed the effects of obstructions on radio signals; however, propagating radio signals reliably inside confined spaces adds an entirely new dimension. Due to the proximity of obstructions in a building environment behavior such as reflections, diffraction around sharp corners, or scattering from walls, ceilings, or floor surfaces will occur.

A.3.1 Radio Frequency Propagation Within a Building

Numerous variables complicate radio coverage in a building environment. To determine radio coverage inside a building, a system designer or planner needs to have crucial information about the building's construction, density, and the specific locations where communication is required. The orientation to the transmitter will affect signal coverage within the building in several ways. First, underground areas may not receive the signal without implementing specific underground coverage solutions. Secondly, multistory buildings will have coverage that varies from floor to floor. It is not uncommon for a 30th floor office to have better radio reception than a similar office on the 1st floor.

In a building environment, obstructions are classified into two categories—hard and soft partitions. Hard partitions are the physical and structural components of a building such as the building layout, room dimensions, doorway openings, and window locations. On the other hand, obstacles formed by the office furniture and fixed or movable structures that do not extend to a building's ceilings are considered soft partitions. Radio signals effectively penetrate both kinds of obstructions in ways that are difficult to predict. Each time the signal passes through an obstacle, the signal strength is reduced. This is also true for floor-to-floor transmissions and underground transmissions. As indicated in the discussion in Section A.2.2—Material Characteristics, a general rule of thumb is that as the thickness of the obstacle increases, the successful transmission of energy through the obstacle will decrease.

Coverage prediction is complicated further by movement of people and objects within the building. Multiradio S.A. found a study discussing the effects on radio coverage due to crowds of people. Tests were conducted with a point source antenna distribution system in a building to determine coverage requirements for 800 MHz and 1.9 gigahertz (GHz) systems. The study found that changes in the density of people caused signal variations as high as 30 decibels (dB).

A.3.2 Radio Frequency Propagation within a Tunnel

Similar to in-building coverage, in-tunnel coverage is difficult, at best, to predict with certainty. Some important factors in determining tunnel radio coverage are the configuration of the tunnel, the materials used to build the tunnel, and the relative orientation of the receiver to the transmitter when the transmitter is located outside the tunnel.

The configuration of the tunnel plays a crucial role in determining the radio coverage. If the tunnel is generally straight and the antenna is located in the tunnel, the signal's primary component will be a result of line of sight (LOS) transmission. As the tunnel changes direction, the signal experiences more loss due to reflections and scattering. The more abruptly the tunnel changes direction, the greater the multipath loss is, and the lower the signal level will be. Furthermore, the losses the signal will experience will be driven by the electrical characteristics of the materials used in the tunnel construction.

APPENDIX B—GLOSSARY OF TERMS

APPENDIX B—GLOSSARY OF TERMS

To understand the problems associated with in-building or in-tunnel radio coverage, it is important to know the vocabulary used to describe the phenomena.

- **Absorption**—Figure B-1 illustrates absorption, which occurs when a radio wave encounters an obstacle that allows RF to pass through, to some degree, to radio waves. When a radio wave strikes the obstacle, part of the radio signal's energy dissipates as heat. This is called absorption. When a radio wave reaches an obstacle such as a wall, the obstacle's material absorbs and reflects portions of the radio frequency (RF) energy.

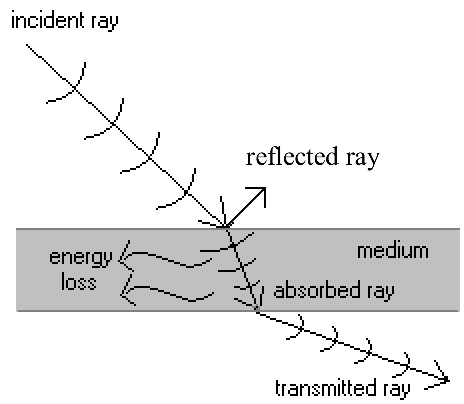

Figure B-1
Absorption

- **Conductivity**—The ratio of current density in a conductor to the electric field causing the current to flow, the ability to transmit electricity.

- **Decibel—**This unit is commonly used to express relative difference in power or intensity, usually between two signals, equal to 10 times the common logarithm of the ratio of the 2 levels. The decibel is usually abbreviated as dB.

- **Diffraction—**Figure B-2 illustrates diffraction, which occurs when the transmission path between the transmitter and the receiver is obstructed by a sharp edge, such as a wall or doorway. Once the wave strikes the surface edge, diffraction occurs (i.e., the wave bends). The resultant signal coverage past the point where the diffraction occurred is now defined by shadowing.

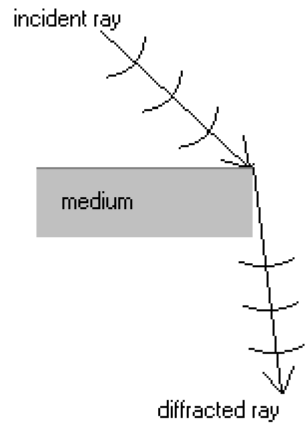

Figure B-2
Diffraction Around a Corner

- **Frequency—**The number of complete cycles per unit time of a complete waveform, usually measured in Hertz. Hertz is a unit of measure that means "cycles per second." So, frequency equals the number of complete cycles occurring in one second.

- **Permeability**—The ratio of the magnetic flux density in a material to the external field strength. The permeability of free space is also called the magnetic constant.

- **Permittivity**—A measure of the ability of a material to resist the formation of an electric field within the material. Also called dielectric constant, relative permittivity.

- **Reflection—**Figure B-3 illustrates reflection, which occurs when a propagating electromagnetic wave strikes an object that is very large (e.g., the surface of the Earth, buildings, or walls) compared with the wavelength of the propagating wave.

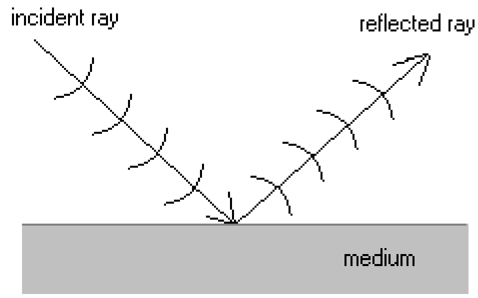

Figure B-3
Reflection

- **Scattering—**Figure B-4 illustrates scattering, which occurs when a propagating electromagnetic wave strikes an object that is very small (e.g., foliage, street signs, and lampposts) compared with the wavelength of the propagating wave. Scattered waves are produced by rough surfaces, small objects, or by other irregular obstructions. The nature of this phenomenon is similar to reflection, except that the radio waves are scattered in many directions. Of all the previously mentioned phenomena, predictions of scattering effects are the most complex.[5]

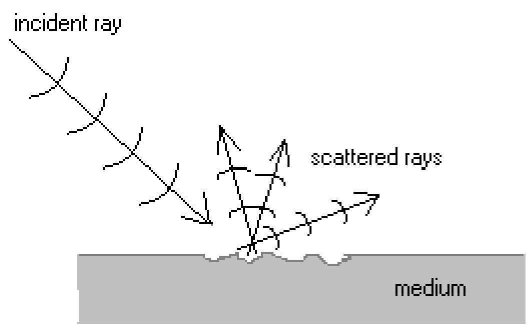

Figure B-4
Scattering Due to a Rough Surface

5 This graphic has been included for illustrative purposes and is not drawn to scale.

- **Shadowing**—Figure B-5 illustrates shadowing, which is the result of an electromagnetic wave being diffracted by an obstruction. The angle of incidence will determine the angle of diffraction and how the wave propagates behind the object. The area immediately behind the object is said to be in the "shadow."

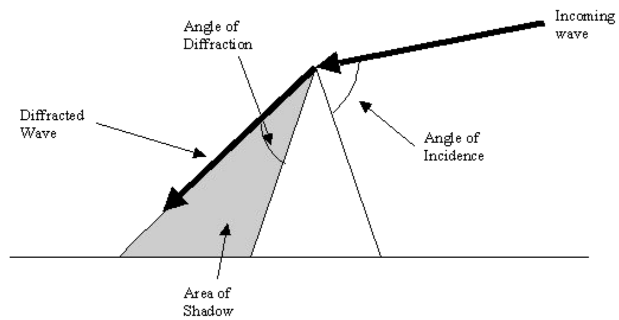

Figure B-5
Shadowing behind an object

- **Susceptibility**—The dimensionless quantity describing the electromagnetic effect on a material when subjected to an electromagnetic field. A high susceptibility rating makes a coaxial cable a poor choice for a distribution system when used in an intense electromagnetic environment.

- **Wavelength**—This is the measure of the distance between one peak or crest of a wave of light, heat, or other energy and the next corresponding peak or crest.

APPENDIX C—TECHNICAL REFERENCES

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