CHAPTER IV: STRUCTURE COMMUNICATIONS ISSUES

Buildings and other structures pose difficult problems for wireless (radio) communications. Whether communication is via hand-held radio or personal cellular phone, communications to, from, and within structures can degrade depending on a variety of factors. These factors include multipath effects, reflection from coated exterior glass, non-line-of-sight path loss, and signal absorption in the building construction materials, among others. The communications problems may be compounded by lack of a repeater to amplify and retransmit the signal or by poor placement of the repeater. RF propagation in structures can be so poor that there may be areas where the signal is virtually nonexistent, rendering radio communication impossible. Those who design and select firefighter communications systems cannot dictate what building materials or methods are used in structures, but they can conduct research and select the radio system designs and deployments that provide significantly improved radio communications in this extremely difficult environment.[4]

Communication Problems Inherent in Structures

MULTIPATH

Multipath fading and noise is a major cause of poor radio performance. Multipath is a phenomenon that results from the fact that a transmitted signal does not arrive at the receiver solely from a single straight line-of-sight path. Because there are obstacles in the path of a transmitted radio signal, the signal may be reflected multiple times and in multiple paths, and arrive at the receiver from various directions along various paths, with various signal strengths per path. In fact, a radio signal received by a firefighter within a building is rarely a signal that traveled directly by line of sight from the transmitter. In general, the radio signal received by a firefighter's radio is the combination of a number of radio signals from different directions. This phenomenon can have the effect of nulling or canceling the signal of interest and result in a temporary loss of the radio link. The sources of these various component radio signals are:

- Diffraction – occurs when radio signals hit the edge of an object causing the radio waves to bend around the object.
- Reflections – occurs when radio signals hit an object that acts as a conductor, such as a metal post, or a dielectric; a perfect conductor reflects all RF signals while a perfect insulator reflects none.[5]
- Scattering – occurs when radio signals hit nearby small objects such as lighting fixtures or even bumps on a rough wall.

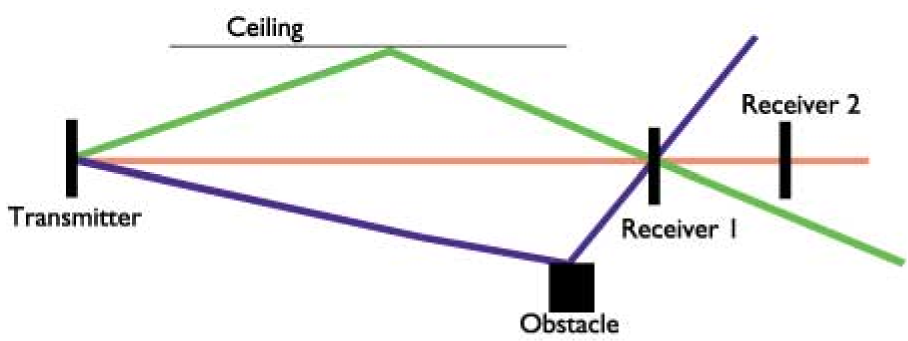
The individual signals caused by reflection, diffraction, and scattering that arrive at the firefighters radio are collectively known as multipath signals. Multipath is a set of

[4] It is, however, not inconceivable that building features affecting emergency communications might be a consideration in building design or even codes in the future.
[5] Neither perfect conductors nor perfect insulators exist. In the real world, most materials act as dielectrics.

reflections and direct waves, with each of these multipath signals traveling a different path to the radio. These paths will have different lengths and different number of reflections and are characterized by varying signal strengths caused by passing through materials that reflect (and absorb) differing amounts of energy. The results are unpredictable delays in transmission and increased attenuation and time dispersion, or a "smearing" or spreading out of the signal

When these various signals combine in the receiving radio, the randomly phased signals add together (Figure 1).[6] Depending on the exact phases the resulting radio signal can increase or essentially disappear. This effect is called multipath fading. Even in cases in which there is a strong signal and a direct line of sight to the receiver, it may be impossible to use a radio due to multipath fading. For example, radio wave propagation inside a building with materials that reflect RF energy efficiently (e.g., metallic materials) can have areas where the signal essentially disappears because the reflections are large enough to effectively cancel the direct radio signal.

FIGURE 1: MULTIPATH REFLECTIONS COMBINE AT THE RECEIVER



Source: IEEE Internet Computing Online.
http://www.computer.org/internet/v6n1/fig3.htm.

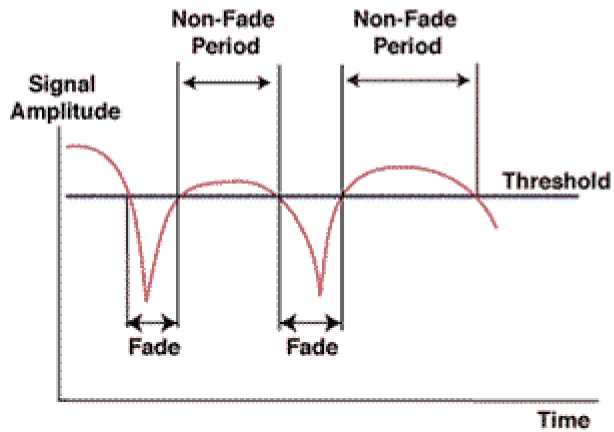
Multipath signals (that is, reflection, scattering, and diffraction) also cause radio signal distortion (noise) as well as additional signal propagation losses (attenuation). Figure 2 shows two key properties of multipath fading, amplitude and period. The fading amplitude is the amount of signal amplification or reduction and is a function of position. Fading period, the time between fades, is a function of speed (both the firefighters' movement and the speed of moving objects, if any, from which multipath signals are reflecting). Because fading level varies by physical position, frequently a firefighter needs only move a few inches to get a 20-dB change in signal, for better or worse. [**243**] Advanced automatic gain control (AGC) techniques have been developed to compensate for this effect, thereby increasing the operational dynamic range of the receiver. Even

[6] Radio waves are characterized as sine waves. When the signal is reflected off of a surface, it travels a longer path to its destination. As a result, the reflected radio wave may arrive at the receiver at a different point in the sine cycle. This cycle offset is referred to as *phase*.

these systems, however, usually operate with fixed time constants that cannot fully compensate for the effects when the signals vary quickly.

On the other hand, because the firefighter is moving slowly and the objects around him remain stationary, the fading period can be long. In other words, a slowly moving firefighter can remain in a fade area. In digital communications, this situation can lead to periods of time where the error rates are too high to be corrected by error-correcting algorithms and result in unintelligible voices or lost communications. In analog systems, this fading phenomenon is exhibited in noise and static. The human brain acts as the correction algorithm in this case. But the brain tries to synthetically "fill in the gaps" based on contextual factors and, while it performs this error correction at a remarkable level, the listener may misconstrue messages.

FIGURE 2: FADING RATE AND AMPLITUDE



Source: Georgia Institute of Technology, Smart Antenna Research Laboratory
http://users.ece.gatech.edu/~mai/tutorial_multipath.htm

It is impossible to find a building that does not have multipath reflections, diffraction around sharp edges, or scattering from wall, window, ceiling, or floor surfaces. As noted earlier, a perfect conductor reflects 100 percent of RF energy while a perfect insulator reflects none. In practice, most materials act like dielectrics that partially reflect (with a 180-degree phase shift) and partially refract (transmits through the material and then bends) signals incident upon them. Metallic walls are the best reflectors in buildings, but in practice even insulating materials cause significant reflections. An all-wood or all-fiberglass structure is better for radio propagation than the typical building, but it too will still have reflections, multipath, and other radio propagation disturbances that make communication worse than outdoors.

Propagation effects also become worse in large buildings, such as high rises, or in other large, complex structures. As the number of obstacles the radio signal passes through increases, such as the successive floors of a high-rise building, the signal degrades from multipath reflection, diffraction, and scattering. The signal strength will vary considerably from position to position on a particular floor as a result of the changing phases and signal strengths of the various multipath signals from within the building and from nearby buildings. [**290**] Consider the transmission geometries as a signal propagates from ground level to a receiver located on the opposite side of a high-rise building. In this case, the signal strength will degrade significantly. Houses and other smaller residential structures are typically less problematical as they are constructed largely of insulators that reflect less efficiently, such as wood, and have fewer reflective surfaces (less floors, furniture, and walls). Unfortunately, it is presently impossible to effectively reduce multipath through building design.

In general, multipath fading is a major contributor to inadequate radio operation inside buildings.

NON-LINE-OF-SIGHT PATH LOSS

One of the largest causes of signal degradation is non-line-of-site (NLOS) path loss. As discussed above, it is common for communications in structures that no direct path exists from the transmitting radio to the receiving radio. Signals radiating from the transmitting antenna reach the receiving radio only by hitting obstacles and reflecting. In a simple structure such as a residential building, it may only take one or two reflections to reach the receiving radio. In a more complex building, the reflections can number orders of magnitude higher. The result of the reflections is an increase in distance that the signal travels between transmitter and receiver. In outdoors situations, the path losses are inversely proportional to the distance traveled raised to the fourth. Indoor path loss is higher.If the path traveled is doubled by reflections, the loss will be at least 16 times greater than if the direct path had existed. The NLOS path distance could easily be much more than twice the direct path in a high rise.

ABSORPTION

Another source of poor radio performance can be signal absorption by building materials. NIST has performed extensive studies of electromagnetic signal attenuation in construction material from 0.5 to 8.0 GHz. [**78,79,80**] The results have shown that the majority of building materials are relatively transparent to electromagnetic signals for the application of using RF to survey through walls. For example, a 1-milliwatt (mW) broadband pulse (0.5 to 2.0 GHz) will penetrate slightly less than 2.5 feet of reinforced concrete and still be above the noise floor of a typical receiver. Wood or concrete block, with its hollow cores, absorbs much less signal than poured concrete and, therefore is easier to penetrate and causes less problems to radio communications. In general, signal attenuation from absorption increases with increasing frequency. Thus, lower frequencies such as very low frequency (VLF) and medium frequency (MF) bands will penetrate building material and even earth to a considerable distance, while 800-MHz ultra high frequencies (UHF) will not. Unfortunately, due to historical factors and spectrum use regulated by the FCC, firefighter radio communications generally operate at frequencies between 100 and 900 MHz. With these frequencies, cumulative signal attenuation can be a serious problem.

BUILDING CONSTRUCTION

Modern construction methods and materials for large commercial buildings have changed quite substantially and can be a source of poor radio performance. Curtain-wall construction (today's approach for large high-rise buildings) means that the walls are “hung” from the structure (typically steel). The walls are generally glass, frequently reflective to radio signals. The glass material used in the windows themselves is RF friendly, but the windows usually contain tinting using a metallic-based composite embedded in the glass which can significantly shield and reflect radio signals. Even when pre-cast concrete panels are used as the “curtain,” there will be lots of “ribbon” window area. Steel or some other metal will be the superstructure. The steel may become a problem at frequencies where wavelengths are twice the distance between the structural beams or longer. The reflective coatings on the large window surfaces, usually metallic, are also culprits in poor radio performance.

The large number of stories that modern construction methods allow also affects radio performance. Building height contributes several factors that degrade communication in structures: NLOS propagation to and from the exterior ground level; and propagation through more building materials (floors, walls, etc.) which increases the absorption, reflection, and refraction of the radio signals off and through these materials. These factors increase distances traveled by signals and exacerbate multipath fading conditions and create the need for repeaters (see below).

By contrast, even though older buildings are usually thick-walled construction they often are more easily penetrated by radio waves because of the different materials used in their construction. Support for upper stories may also include a substructure separate from the walled construction, but not to the same extent as current high-rise construction. Many older buildings have thicker walls, because the walls are the primary support. However, buildings constructed in this manner usually are not tall, perhaps four or five stories. Older buildings with thick masonry walls, especially of concrete, can cause radio reception problems from absorption. But because their construction limits the number of stories, radio signals need only pass through a few floors to reach the firefighters within.

On the surface, it would appear that transmission in older concrete-based buildings should not be a problem; however, many older buildings indeed are not conducive to radio communications. While each building is unique and requires careful modeling to fully understand the propagation characteristics, several common factors can impede radio transmission within these structures, including:

- Many older buildings have replaced windows with newer tinted products.
- Fiberglass insulation, even in wood structures, often has a metallic backing.
- Older lead-based paints used on interior walls may still exist in the under-layers of paint.
- Metallic furniture is still in common use today. This furniture includes desks, shelving, and cabinets—virtually all office file cabinets are constructed from metal.

- In addition to rebar, concrete reinforcing wire mesh may be used in older buildings to provide increased strength and to mitigate building damage from environmental hazards such as earthquakes. While the mesh in general may somewhat impede radio transmission, in some cases it may be worse than others depending on the size and geometry of the mesh patterns in relation to the wavelength of the radio transmission.
- The majority of internal wall construction today in office buildings today use drywall-over-steel framing material. Internal office build-out in even the oldest buildings frequently changes with new tenants or new requirements.

So even in structures where the inherent building properties may appear to be more RF friendly, multiple factors can affect transmission

Studies have found that placement of repeaters that amplify and retransmit radio signals can have a large impact on coverage within a building. [**244,290**] For example, a repeater positioned such that the radio waves strike the building façade directly at a 90-degree angle results in very little energy reflecting from the surface. Except for the absorption characteristic of the material, the radio signal passes through to the building interior. Signals that graze the surface of a building have greater reflection off the façade and fewer signals entering the building. The result can be poor radio coverage even on a floor at the same height as the repeater. Experience has shown that placing a repeater on the roof of a building can provide the best coverage in many cases as the signal enters the building at a near 90-degree angle and avoids the typical coated, reflective glass on today's modern office buildings. [**244,290**]

RADIO SYSTEM CONSIDERATIONS

The problems inherent in radio communications into, from, and within structures should be addressed on several fronts whenever possible. Some of the options are:

- *Radio system design* – Provide redundant paths for each receiver if at all possible. [**308**]

- *Antenna system design* – Accommodate dual-diversity antennas used at each receiver at a minimum. Provide sufficient repeater antenna gain for hand-held radio transmissions to be received by the incident commander. Place repeater antennas properly. [**308**]

- *Signal/waveform design* – Incorporate techniques that mitigate multipath, such as spread spectrum radio design with high signal-to-channel bandwidth ratio. Example spread spectrum waveforms currently in use to combat multipath are CDMA (common in cellular systems), ultra wideband (UWB) in development for robust in-building communications and "see-through walls" radar products, frequency hopping (available in emergency personnel evacuation paging systems), and OFDM (used for television broadcast applications and in-building radio location systems currently being developed). Other options include using narrowband multipath reduction digital signal processing algorithms, such as equalization. These algorithms essentially function as AGC circuits that are designed and implemented in digital signal processors. These algorithms (and circuits) can remove the deep amplitude notches that otherwise occur from fading.[7][**308**]

- *Building/environment design* – Firefighters cannot dictate building methods or materials, but they may be able to influence modifications for their use. For example, leaky feeder cable could be built into structures for firefighters, HVAC systems could be specially modified to act as waveguides [**164**] for firefighter communications, or a method to communicate by coupling RF signals onto the ac power lines in a structure could be provided. [**308**]

Signal absorption can be addressed directly if it is possible to select a radio frequency that has minimal absorption in construction materials or has other characteristics to allow penetration of structures. Medium frequency waves penetrate building materials more readily and can parasitically couple to building conductors such as telephone lines or ac power lines, both of which can act as a distributed antenna within the structure. [**115, 116,128,129,130,175,198,211,288**] Another way to address signal absorption is to begin with more radio transmit power and higher gain antennas. A mobile repeater properly sited at a fire scene will help get signal into a building, but because the firefighters' hand-held radios have limited transmit power, the repeater needs to have a high-gain antennas to enhance the reception of communications from the firefighters within the structure.

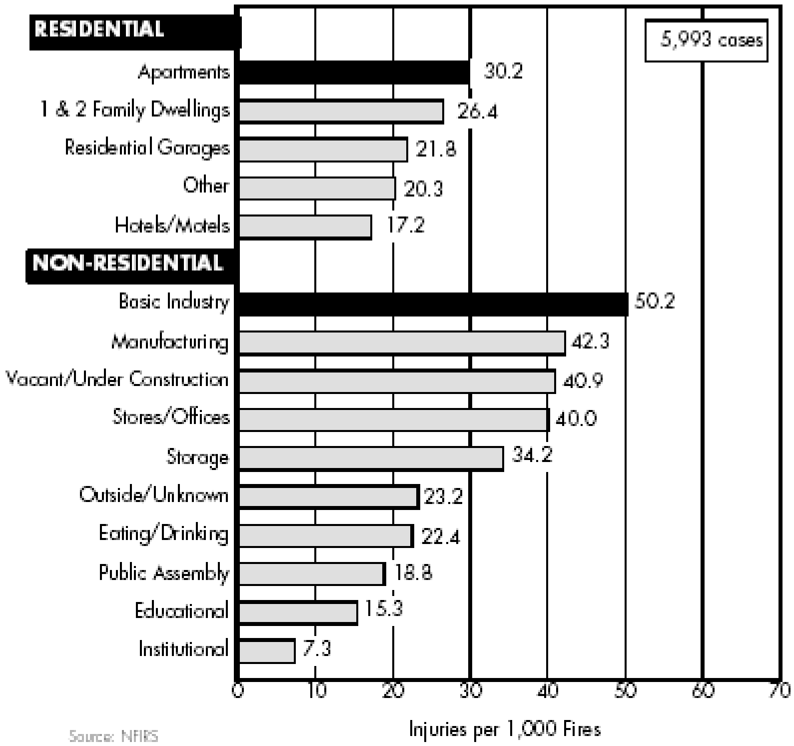
In general, the radio systems used by firefighters do not have the required features for operation in difficult indoor areas.

Risk to Firefighters

As a result of the radio communications problems inherent in structures, high-rise structures, as well as warehouses and other non-residential structures, pose the greatest challenges to firefighter radio communication. These buildings tend to be those where communication problems are of most concern. While fires are fewer in number in these properties than in typical one- and two-family dwellings, firefighters are at greatest risk in these buildings. As illustrated in Figure 3, basic industry, manufacturing, vacant buildings and construction sites, retail stores and commercial offices, storage facilities, and apartment buildings rank higher in risk of injury to firefighters than the typical home.

[7] The AGC design and associated time constants need to be carefully selected as to not impair the signal-to-noise ratio of the signal or saturate components in the receiver chain.

FIGURE 3: FIREFIGHTER INJURY RATE IN STRUCTURES



Source: *Fire in the United States 1989-1998*, United States Fire Administration

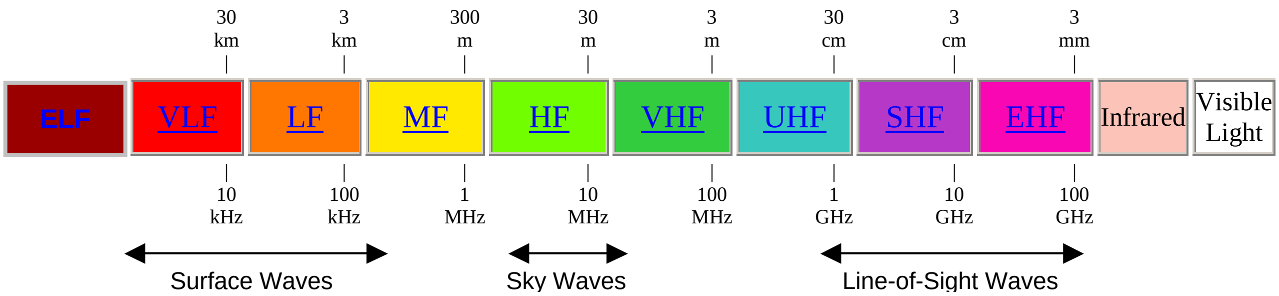
Radio Spectrum Considerations

The radio spectrum is the lowest end of the larger electromagnetic spectrum. This energy spectrum ranges from radio waves to gamma rays. Radio waves, visible light, X-rays, and all the other parts of the electromagnetic spectrum are fundamentally the same thing. They are all electromagnetic radiation that travels and spreads out as it goes (called propagation) and can be expressed in terms of energy, wavelength, or frequency.

RADIO FREQUENCY BANDS

The radio spectrum is segregated into frequency bands, each with propagation characteristics and regulated uses. The use of these frequencies bands in the U.S. is licensed and regulated by the Federal Communications Commission (FCC). The use of all radio frequencies (and equipment) is determined by the rules and regulations issued by the FCC in conjunction with the National Telecommunications and Information Administration (NTIA). All radio users must abide by them. Much of the current assignment of frequencies is founded on historical use and not necessarily on the optimum assignment of the spectrum, based on the physical properties of the spectrum, to specific applications.

FIGURE 4: RADIO SPECTRUM



Source: Adapted from Allocation of Radio Spectrum in the United States, http://www.jneuhaus.com/fccindex/spectrum.html#table_of_contents

Lower frequencies propagate further than higher frequencies, both through the air and into the ground. For propagation through the air, the spectrum can be divided into three sub-spectra by the type of propagation exhibited:

- *Surface*: The longest electromagnetic waves, below 500 kHz, tend to follow the curvature of the Earth, guided between the Earth and the ionized layers of the upper atmosphere (i.e., the ionosphere).
- *Sky*: High frequency waves, 3–30 MHz, are reflected by the ionosphere and are capable of propagation around the Earth.
- *Line-of-sight*: Above 1 GHz, electromagnetic waves behave much like light propagating through a clear, reasonably uniform atmosphere. When originating from a point source, they propagate in all directions.

The intermediate frequencies from 500 kHz to 3 MHz and 30 MHz to 1 GHz are transition bands where the propagation characteristics in the atmosphere are more complex.

Despite the propagation advantages, a disadvantage of the lower frequency bands, however, is the limited amount of available spectrum. At very low frequency (VLF) the spectrum available for public safety radio is only 27 kHz. This is barely enough to pass a single analog voice channel. As a result, this band is primarily used for applications that only require low-speed data transmission. By contrast, the super high frequency (SHF) band has 27 GHz of spectrum, a million times the available spectrum at VLF, but it suffers from poor propagation characteristics. Also, radio equipment, particularly antennas, is frequently larger at lower frequencies. As a result, the equipment to support the use of these frequencies may be too cumbersome to be practical on the fireground. Table 6 shows some of the basic uses of the frequency bands and some of the more relevant propagation characteristics.

TABLE 6: RADIO FREQUENCY BANDS

Band	Frequency Range	Wavelength	General Applications	Major Propagation Characteristics
ELF	300–3000 Hz	100–1000 km	Navigation, long distance communication with submarines	Wave tube between Earth surface and the ionosphere
VLF	3–30 kHz	10–100 km	Navigation, long distance communication, emergency paging	Ground propagation; stable
LF	30–300 kHz	1–10 km	Navigation, long distance communication with ships	Ground propagation; stable
MF	300–3000 kHz	100–1000 m	AM broadcasting, radio navigation, powerline communications, mine voice communications	Ground-wave, sky-wave propagation; fading
HF	3–30 MHz	10–100 m	Radio broadcasting, fixed point-to-point (around the world)	Large perturbation, reflection in ionosphere
VHF	30–300 MHz	1–10 m	Radio & TV broadcasting, mobile services	Diffraction
UHF	300–3000 MHz	10–100 cm	Cellular telephony (GSM, NMT, AMPS), fixed point-to-point, satellite, radar	Shadowing by mountains and building
SHF	3–30 GHz	1–10 cm	Broadband indoor systems, microwave links, satellite communications	Attenuation due to rain, snow, and fog
EHF	30–300 GHz	1–10 mm	LOS communication (short distance or satellite)	Attenuation due to rain, snow, and gases

Source: Adapted from http://www.s3.kth.se/radio/COURSES/RKBASIC_2E1511_2001/lecture_1.pdf.

Satellites operate at ultra high frequency (UHF), super high frequency (SHF), and extremely high frequency (EHF). Table 7 shows the various frequencies and examples of some of the major satellites that operate in these bands. The frequencies represent typical uplink and downlink transmissions.

TABLE 7: SATELLITE FREQUENCY BANDS

Band		Frequency Range	Bandwidth	User	Satellites
UHF		200 – 400 MHz	160 Hz	Military	FLTSAT, LEASAT
	L	1.5 – 1.6 GHz	47 MHz	Commercial	MARISAT, INMARSAT
SHF	C	6/4 GHz	800 MHz	Commercial	INTELSAT, DOMSATS, ANIK E
	X	8/7 GHz	500 MHz	Military	DSCS, SKYNET, NATO
	Ku	14/12 GHz	500 MHz	Commercial	INTELSAT, DOMSATS, ANIK E
	Ka	30/20 GHz	2500 MHz	Commercial	JCS
			1000 MHz	Military	DSCS IV

Band		Frequency Range	Bandwidth	User	Satellites
EHF	Q	44/20 GHz	3500 MHz	Military/DOT	MILSTAR
	V	64/59 GHz	5000 MHz	Military	CROSSLINKS

The applications and potential applications of these frequencies are undergoing a rapid transformation with the growth of technological developments occurring in modern communications. Recent developments in digital signal processing algorithms and powerful, inexpensive, small hardware allow communication systems to be built that can use the spectrum in new ways. Systems can be built that use the narrow bands at the lower frequency end of the spectrum to transfer much more data or many more voice channels than previously possible. Another new technology, ultra wideband communications, uses broad swaths of the spectrum across more than one band. These new technologies are forcing the FCC to consider changes in spectrum allocations to accommodate the new spectrum users. In spite of the apparent abundance of spectrum for many applications, the lack of sufficient and appropriate spectrum remains a major issue.

In June 1995, Congress empowered the Public Safety Wireless Advisory Committee (PSWAC) to specifically address issues relating to spectrum needs and uses for the public safety community. The PSWAC determined a short-term need for an additional 2.5 MHz of spectrum, and long-term need for an additional 25 MHz of spectrum for public safety use. The Balanced Budget Act of 1997 mandated the reallocation of 24 MHz of broadcast television spectrum by December 31, 2006, for public safety uses. However, this will not solve the frequency congestion issues in the near term as the Act includes provisions for extensions beyond 2006 if the penetration of digital television service in a given market is less than 85 percent.

As a result, the uncertainty of when and if this spectrum will become available severely limits planning by the public safety sector and causes reluctance in manufacturers to invest in products and technologies for this spectrum.

The current bands and primary allocated users are outlined below:

Extremely Low Frequency (ELF) – The ELF band is primarily used by the Navy to contact submarines deep under water, depths that normal radio waves cannot penetrate. (Water absorbs high frequencies.) The low frequency, however, cannot broadcast much useful information. As such, the Navy only uses the ELF system to signal their submarines to come closer to the surface, and then broadcasts the actual message by other means. There has been some controversy about the human health effects of ELF. This is a relatively new band designation.

Very Low Frequency (VLF) – The VLF band is very narrow, only 27 kHz, and currently allocated for uses such as low-data-rate power line communications by a power utility for general supervision of the power system and cable locating equipment. Radio waves in this band can propagate by surface waves over long distances in the air and ground waves penetrating long distances through the earth. At one time, these frequencies were used by commercial interests to transmit and receive the majority of “wireless” message traffic in a large network of stations, but today only a handful of military and government stations remain on the air on a regular basis. The narrowness of this band has limited the use of the VLF band for fireground communications to applications such as a one-way emergency evacuation paging system.

Low Frequency (LF) – The LF band covers 270 kHz from 30 to 300 kHz and is currently used for applications such as marine and aviation navigation beacons, low-data-rate power line communications, and cable locating equipment. This band is also used by European broadcast radio for its ability to “hug the earth,” eliminating shadowing by mountains.

Medium Frequency (MF) – The MF band is from 300 kHz to 3 MHz. This band currently includes AM radio (535 to 1605 kHz or almost half of the band), radio navigation, and various others. Land mobile public safety (fire, police, etc.) agencies are allocated several hundred kilohertz in this band. MF signals are useful in that they can propagate over fairly substantial distances (e.g., two mobile units could easily talk to one another with tens of miles of separation). However, the signals may have problems propagating through steel-reinforced structures. MF RF has been shown to have an ability to inductively or parasitically couple to conductors such as telephone and ac power lines or the steel tracks used for underground mining vehicles. [**115,116,128,129,130,175,198, 211,288**] This type of coupling has been used to communicate for thousands of feet in underground mines. Miners and cave explorers have used MF for communications because of its ability to travel through the earth and solid rock.

High Frequency (HF) – The HF band is used for long-distance communications because of its sky-wave propagation mode. The band is allocated in large part to maritime radiotelephone, amateur radio, and flight test stations. The new broadband power line communications products for in-house LAN use (e.g., HomePlug 1.0) and backhaul to the Internet, access power line communications (PLC), over the medium-voltage power grid operate in this band as well. Organizations such as the American Radio Relay League (ARRL) are fighting access PLC use of the HF band with the FCC.

Very High Frequency (VHF) – Radio astronomy, cordless telephones, amateur radio, FM radio, television, aviation, and public/private land mobile make up a large portion of this band.

Ultra High Frequency (UHF) – Radio location, new 700-MHz public safety band, television, satellite communications, military and other government communications, maritime communications, and public and private land mobile are some of the users of this band.

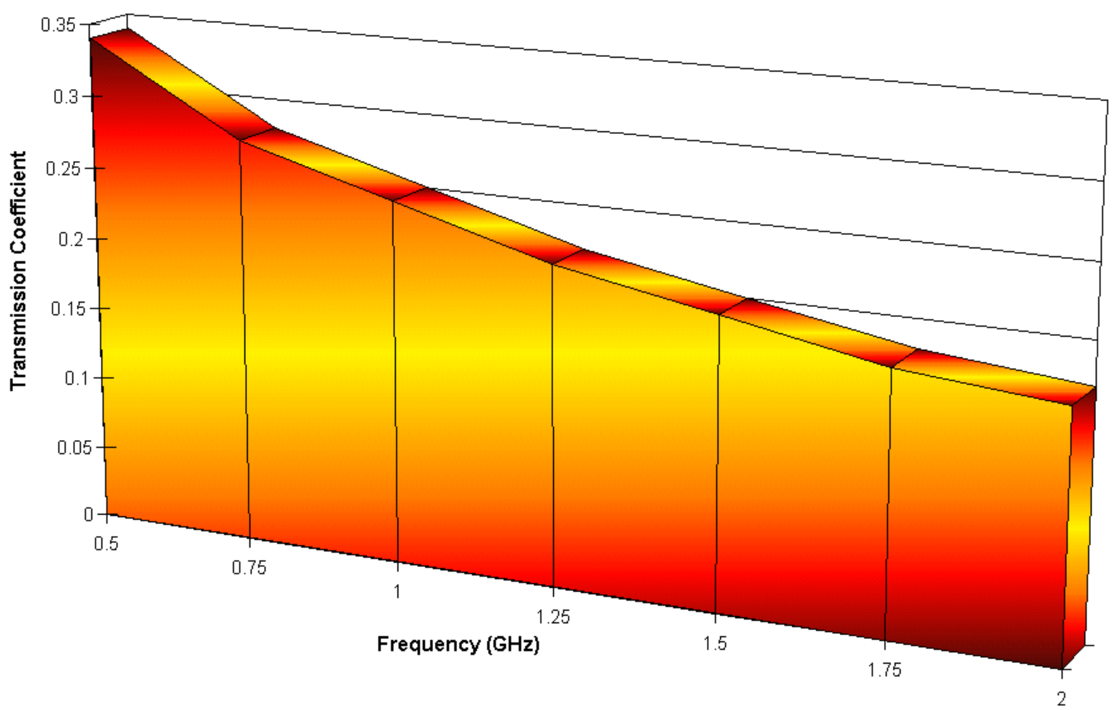
Super High Frequency (SHF) – Radio location, radio navigation, point-to-point microwave, and satellites are users of this band. This band has unlicensed frequencies.

Extremely High Frequency (EHF) – Specialized satellite. Much of this band is proposed for services but is not currently allocated.

PROPAGATION

For propagation through earth, building material, and structures, the picture is complex and not easily categorized. As noted under the discussion of absorption, a significant amount of work has been done by NIST on RF transmission through building materials for its program on RF surveying for construction automation. [**78,79,80**] In addition to work on signal attenuation through construction materials, the NIST study also characterized power attenuation in relation to material thickness, electrical permittivity, and dielectric constant as a function of frequency. These construction materials included various brick configurations, various mixtures and thicknesses of concrete, interior finishing materials, glass, and reinforced concrete. Measurements of the frequency dependency of the material dielectric and conductivity constants were curtailed due to funding cuts. A sample of the data taken is shown in Figure 5 for the transmission coefficient[8] of a 102-mm-thick section of concrete vs. frequency.

FIGURE 5: TRANSMISSION COEFFICIENT FOR CONCRETE MIXTURE #5



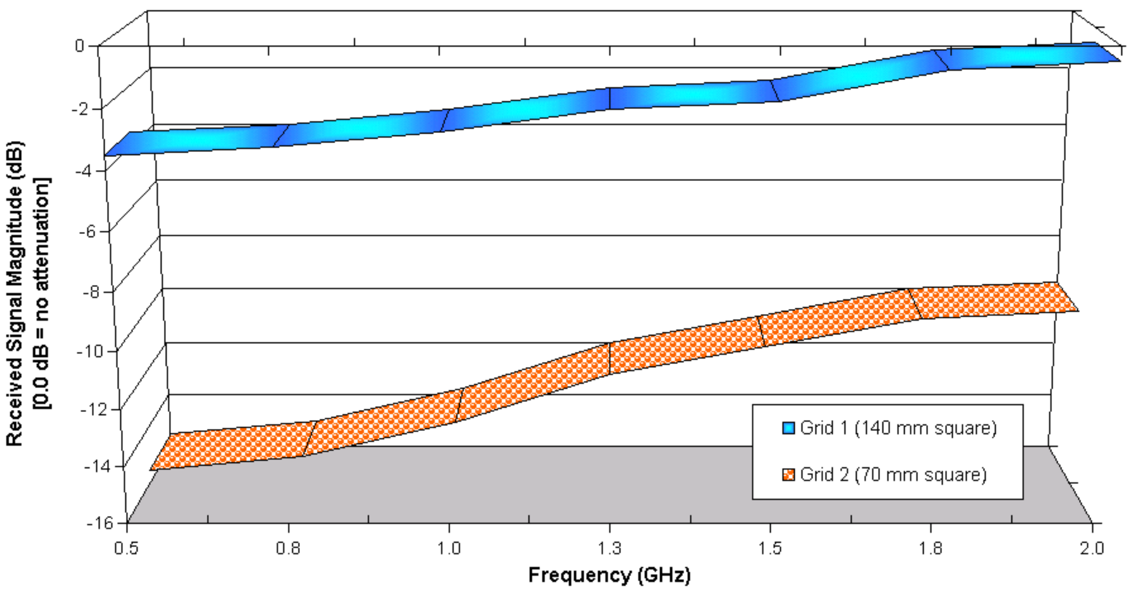
Source: Adapted from NIST Construction Automation Program Report No. 3: *Electromagnetic Signal Attenuation* in Construction Materials, National Institute of Standards and Technology, Gaithersburg, MD. October 1997.

The frequency dependency of RF transmissions in building material does not necessarily mean that the same is true for penetration into structures. Conductive screens with

[8] The transmission coefficient is a measure of absorption. The higher the transmission coefficient, the lower the absorption in the material.

openings of approximately one-half the RF wavelength or smaller attenuate the RF waves heavily. Typical examples of potential barriers to RF signals would be rebar grids in reinforced concrete or the steel support structures used in modern curtain wall buildings. An example of this effect is shown in Figure 6 for transmission through two different rebar grid patterns. [**79**] Both rebar grids are square patterns. Grid 1 had 140-mm spacing and grid 2 had 70-mm spacing. Looking at one frequency, 1.5 GHz, grid 1 is a little larger than a half wavelength (1/2 x 200 mm), but grid 2 is smaller. The figure shows that grid 1 is relatively transparent to this frequency but grid 2 attenuates it heavily, over 10 dB more than the bigger grid. The figure also shows that the attenuation increases with frequency as expected.

FIGURE 6: RF ATTENUATION THROUGH REBAR GRID



Source: Adapted from NIST Construction Automation Program Report No. 3: *Electromagnetic Signal Attenuation* in Construction Materials, National Institute of Standards and Technology, Gaithersburg, MD. October 1997.