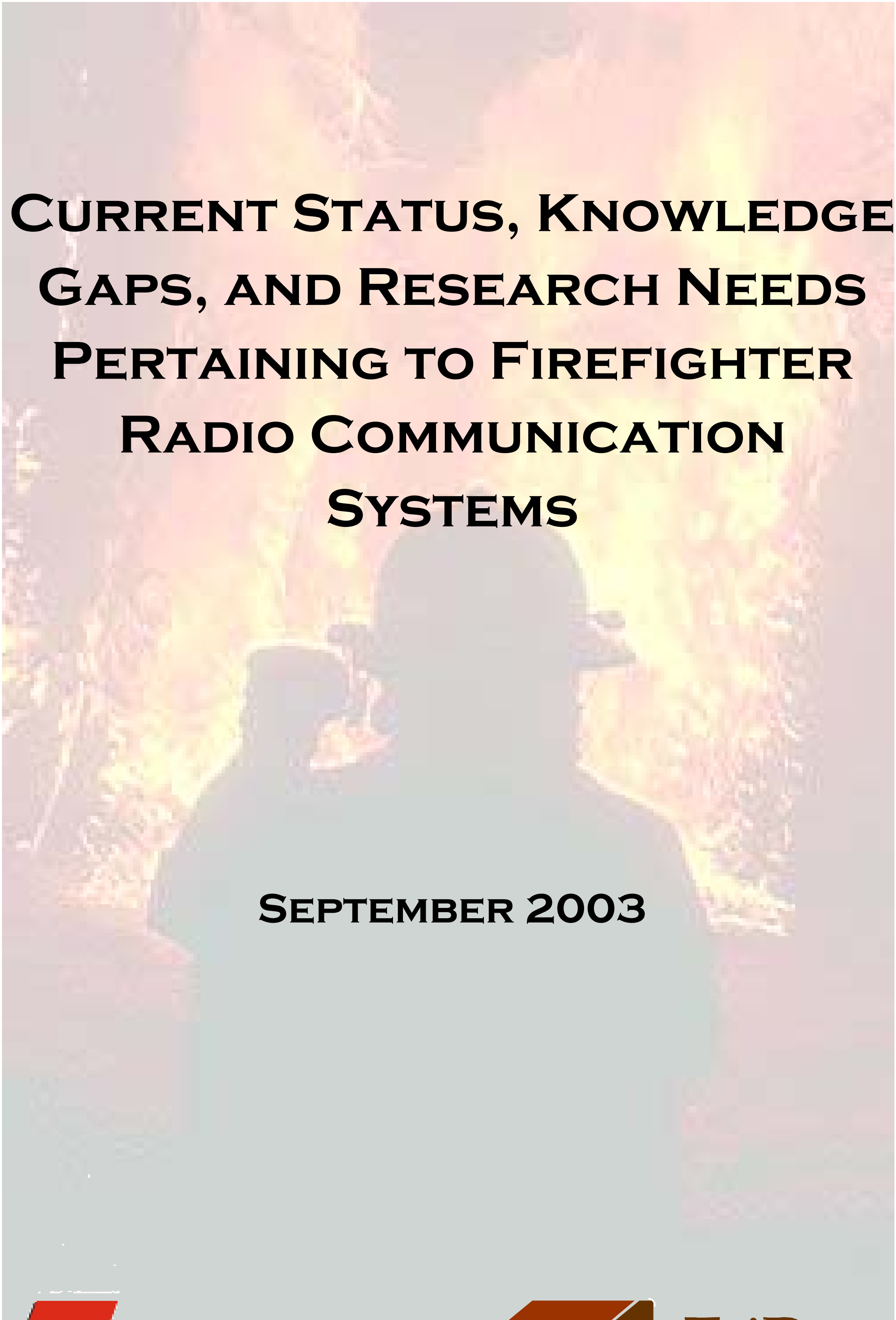

Current Status, Knowledge Gaps, and Research Needs Pertaining to Firefighter Radio Communication Systems

September 2003

NIOSH

TriData

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FINAL REPORT

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Prepared for:
National Institute for Occupational Safety and Health
1095 Willowdale Road
Morgantown, WV 26505

Prepared by:

TriData Corporation
1000 Wilson Boulevard, 30th Floor
Arlington, Virginia 22209

Patricia Frazier, Project Leader
Robert Hooper
Brian Orgen
Nicole Hankin
James Williams

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Contact / Contributor	Company
Vincent Coli	Vice President of Sales, Æther Wire
Louis Hanson	President, LH Enterprises
Patrick Houghton	CEO, Æther Wire
Jack Jarboe	Vice President, Product Development, Grace Industries
Brian Kibler	Senior Account Manager, Motorola
Dr. Peter H. Krawarik	Independent Management Consultant
Nader Moayeri	NIST Information Technology Laboratory
Richard C. Meyers	Director of Communication Networks, System Planning Corporation
Santiago Moreno	Vice President, Portico Architects
Dr. John Newbury	Power Communications Research Group, Open University, Manchester, England
Dr. John Orr	Professor of Electrical Engineering, Worcester Polytechnic Institute
Winston Rice	Consultant, RF Engineering
Lance Rosen	President, Plexeon
Dr. Robert Scholtz	Professor of Electrical Engineering, University of Southern California
Dr. William C. Stone	Leader, Construction Metrology and Automation Group, NIST Building and Fire Research Laboratory
Hal Walls	Vice President of Sales, Transtek
Mike Worthington	Corporate Vice President and General Manager, Motorola

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Contact / Contributor	Affiliation
Reade Bush	Firefighter/Paramedic, Cherrydale Volunteer Fire Department Arlington County, Virginia
Gary Wilks	Communications Technologist, Austin Fire Department Austin, Texas
Frank Snyder	Assistant Chief of Operations, Baltimore Fire Department Baltimore, Maryland
Bill Boyd	Assistant Chief, Bellingham Fire Department Bellingham, Washington
Ken Gustafson	Division Chief, Communications, Bellingham Fire Department Bellingham, Washington
Peter O'Rourke	Superintendent of Fire Alarm office, Boston Fire Department Boston, Massachusetts
Jeff Webb	Assistant Fire Chief, Boulder Rural Fire Department Boulder, Colorado
Bob Parker	Fire Chief, Greater Brighton Fire Protection District Brighton, Colorado
John Schildknecht	Assistant Chief, Broward County Fire Rescue Broward County, Florida
Jeff Stern	Battalion Chief, Castle Rock Fire and Rescue Department Castle Rock, Colorado
James Burke	Deputy Chief, Charlotte Fire Department Charlotte, North Carolina
William Carter	Supervisor, Office of Communications Chicago, Illinois
Jim Wilson	Communications System Manager, Southern Nevada Area Communications Council Clark County, Nevada.
David Kinney	Captain, Fire Dispatch, Dallas Fire Department Dallas, Texas
D.L. Millaway	Assistant Chief of Operations, Dallas Fire Department Dallas, Texas
Abner Garrett	Chief of Communications, Detroit Fire Department Detroit, Michigan
Bill Harp	Firefighter/Driver, Detroit Fire Department Vice-President, Detroit Firefighters Association Local 344 Detroit, Michigan
Jeff Coffman	Deputy Chief, Support Services, Fairfax County Fire Rescue Fairfax County, Virginia
Wes Rogers	Lieutenant, Communications, Fairfax County Fire Rescue Fairfax County, Virginia

Contact / Contributor	Affiliation
Daniel Shoup	Firefighter/EMT, Gettysburg (OH) Rural Fire Department Gettysburg, Ohio
Tom Jones	Chief, Glen Echo Fire Department Bethesda, Maryland
Lou Amell	Chief of Communications, Las Vegas Fire Department Las Vegas, Nevada
Martin Enriquez	Captain, Communications, Los Angeles Fire Department Los Angeles, California
Matthew Partlow	Deputy Chief, Support Services, Loudoun County Fire Rescue Loudoun County, Virginia
CJ Walker	Communications Manager, Memphis Fire Department Memphis, Tennessee
Douglas Holton	Division Chief of Operations, Milwaukee Fire Department Milwaukee, Wisconsin
Steve Souder	Director, Emergency Communications Center Montgomery County, Maryland
Bob Oliver	Deputy Chief, Dispatch and Deployment, Phoenix Fire Department Phoenix, Arizona
Leif Anderson	Captain, Deployment, Phoenix Fire Department Phoenix, Arizona
Peter Micheli	Fire Chief, Pittsburgh Fire Department Pittsburgh, Pennsylvania
Dave Sprando	Assistant Fire Chief, Emergency Operations, Portland Fire Department Portland, Oregon
Mike Schmidt	Battalion Chief, Portland Fire Department Portland, Oregon
Alfred Castro	District Chief, Communications, San Antonio Fire Department San Antonio, Texas
Rodney Hitzfelder	Deputy Chief of Operations, San Antonio Fire Department San Antonio, Texas
Susan Harris	Communications Manager, San Diego Fire-Rescue Department San Diego, California
Bruce Cartelli	Division Chief of Operations, San Diego Fire-Rescue San Diego, California
Paul Chin	Chief of Communications, San Francisco Fire Department San Francisco, California
Richard Sheola	Township Administrator, Springfield Township Springfield, New Jersey
Roger Sutherland	Deputy Director, Stafford County Fire Rescue Stafford County, Virginia
Mike Rudd	Deputy Chief of Operations, Wichita Fire Department Wichita, Kansas

EXECUTIVE SUMMARY

The National Institute for Occupational Safety and Health (NIOSH) commissioned this study to identify and address specific deficiencies in firefighter radio communications and to identify technologies that may address these deficiencies. Specifically to be addressed were current and emerging technologies that improve, or hold promise to improve, firefighter radio communications and provide firefighter location in structures.

Introduction

One of the most significant problems facing firefighters within a structure on the fireground is the ability to communicate reliably between the firefighters themselves and between the firefighters and the command post or communications center. In an ideal world, firefighters would be able to communicate with one another and the command post at all times, regardless of where they are or what they are doing. However, this is not the case. Firefighter radio communications to, from and within structures can be unreliable, thereby compromising the safety of firefighters on the fireground.

Over the past decade, incidents involving firefighter injuries and fatalities have demonstrated that, despite technological advances in two-way radio communications, important information is not always adequately communicated on the fireground or emergency incident scene. Also, the events of September 11, 2001, and other emergency situations in recent years have highlighted the need not only to improve firefighter radio communications, but also the communication systems available to law enforcement personnel, emergency management officials, and other public-safety responders.

The continued incidence of firefighter fatalities where communications are cited as a contributing factor as well as the industry-wide lack of consensus on the appropriate frequencies to use in fireground communications have prompted NIOSH to more thoroughly investigate fire communications and the problems associated with communications within, as well as into and from, structures.

Methodology

To begin the project, the team members compiled a comprehensive set of communications issues that affect radio communications in the fire service from several sources – an initial literature survey, knowledge of the project team members, and discussions with fire service leaders, NIOSH project team, engineers, and others. Team members refined this comprehensive set of issues with NIOSH project personnel to identify critical issues that could be addressed by improvements in radio communications. A prioritized list of communication and personnel location problem areas was developed. In general, the primary focus was clarified to be the identification, status, and research recommendations for technologies that could improve in-building communications or provide firefighter location within structures. Furthermore, the effort was to focus on the radio communications and radio location problems found in large structures such as high-rises to include radio transmissions into and out of the structure to the command post. Buildings such as these present the most difficult communication problems because of their floors both high above the ground as well as basement levels. The list of the high priority topics is shown in Table 1.

TABLE 1: PRIORITY TECHNICAL AREAS AND RELATED TOPICS ADDRESSED IN STUDY

Area	Example Issues
Accountability	• Integrating Personal Accountability Systems (PAS) with communications • Electronic accountability • Automatic vehicle location • Electronic command boards
Communication Planning and Coordination	• Through building (into/out of) • Underground • In building
Monitoring Firefighter Welfare and Location On-Scene	• Role/responsibility of dispatchers • Use of field communications units and communications coordinators • Remote monitoring • Vital signs • Location
Reliability	• Line-of-sight limitations • Underground (subways, parking garages) • Confined space rescue • Communication into and out of buildings (especially high rises) • Intermittence • Communication coverage/dead spots
Interference	• Building construction and materials (such as concrete, metal, and Lexan) • Radio propagation through fire, heat, and smoke • Cell phone towers (e.g., Nextel) • Terrain
Unsuitable Equipment	• Frequency band unsuitable for structure/ground penetration

The first phase of the project was an extensive literature search for research and product information. The literature search covered a wide variety of government, engineering, and scientific databases. The Internet was also used to identify current products as well as the abundance of unpublished research posted by various companies and universities.

The next phase of the project included two areas: identifying communication problems experienced by fire departments and investigating the current state of technology research and development. This research was used in the third phase of the project to identify gaps between the problems and issues of firefighter communications and the technologies to address these issues.

In final phase of the project, recommendations were made for areas of research, which if completed, could lead to improved firefighter communications in structures. The technologies identified in this phase included current applications, potential applications, and how these potential applications could be relevant to firefighter communications.

This phase is addressed in Chapter V, "Current Technology Status, Knowledge Gaps, and Research Needs". Past and current research is described as well as important issues remaining to be overcome if the technology area is to be feasible for firefighters.

Communication Issues

Communication problems commonly encountered by firefighters (and others) can be broadly divided into two categories. First are mechanical or technical issues related to unsuitable equipment, system design, inadequate system capacity (too much radio traffic), and building construction, among others. The second category of problems relates to human factors.

Fire departments consistently have problems maintaining effective communications while operating in large structures, such as high-rise office buildings and apartments, and warehouses. Similar issues exist in structures with a large number of windows (or areas of glass) with reflective coatings. Communications from areas below grade (e.g., basements, parking garages, subway systems, tunnels) tend to be uneven. For the typical home, communications are generally not a problem. The technical issues associated with the physical structures themselves (building materials, height, etc.) are discussed further in the body of the report. Communications problems encountered by fire departments are discussed further in the body of the report. Solutions currently used by fire departments range from increasing the number of repeaters to migrating to trunked communications systems.

Human factors, such as radio discipline, training, and tactical decisionmaking, also affect firefighter radio communications. These factors, while not technical issues themselves, adversely affect communications, especially when combined with technical and equipment issues. These issues, while not under the scope of this report, are discussed as background in the body of the report.

Technology Summary

The literature search identified a number of technologies that could contribute to solving firefighter communications problems. Some of these technologies can be used as standalone technologies while others are technologies that enhance performance of wireless links. Mobile area networks (MANet), ultra wideband (UWB), bi-directional amplifiers (BDAs), power line communications (PLC), medium frequency (MF), very low frequency (VLF), and radio frequency over heating and ventilation materials (RF over HVAC) all can be used standalone to build a communications system. Smart antennas, spread spectrum modulations, channel coding and interleaving, and automated electronic status systems are enhancing technologies.

The ideal technology would provide robust in-building firefighter communications without equipment setup or equipment beyond personal communication devices (e.g., a handheld radio, personal tag, or the like). For providing a practical communications system, this technology does not yet exist. Current firefighter communications suffer from inconsistent in-building performance and may require additional equipment such as repeaters. Untapped technologies provide other opportunities, but have limitations as well. VLF signals have been used to penetrate hundreds of feet through the earth in mining applications but the band is so narrow it can carry only one analog voice channel. MF through-the-air-signaling was tested in England as a means of communicating with firefighters in high-rises. This application used antennas that were looped around the entire building, making the antenna size a serious drawback. Furthermore, neither VLF nor MF has spectrum allocated for this use. A MANet does not require any infrastructure, but it does require that a firefighter always be with in range of a sufficient number of other firefighters who act as a network of repeaters. In practice, this may be impossible as firefighters may be out-of-range of each other in high-rise stairwells or building basements. Other technologies have similar issues.

The next best choice to provide robust in-building fire communications would be one that couples personal communication devices with standard infrastructure found throughout a building (e.g., ac power lines and telephone lines) and little or no portable infrastructure (e.g., repeaters). Such a system would require some setup to interface the personal communication devices with the infrastructure. Using a PLC system would require the firefighters to plug a wire access point (WAP) into the building ac outlets to connect to the building's ac power lines. It may also require a portable range extender to placed as needed. A MANet may require additional fixed wireless nodes (similar to a repeater) to enhance its range.

Another choice would be one that couples the personal communication devices with specially engineered, permanently installed building infrastructure. BDAs and RF over HVAC are examples. If these systems are in place and designed correctly to give the firefighters the coverage required at the frequencies required, they work well.

Using these criteria, the top technologies potentially suitable for firefighter communications are shown below in Table 2. A summary of each of these technologies follows. A complete discussion of these and other technologies investigated is presented in Chapter V.

TABLE 2: SUMMARY OF STANDALONE TECHNOLOGIES WITH POTENTIAL TO IMPROVE IN-BUILDING RADIO COMMUNICATIONS

Technology	Existing Structure		Portable Add-on Equipment for System Enhancement	Limitations	Potentially Applicable Enhancing Technologies
	Built-in Infrastructure Required	Modifications Required			
MANet	—	—	• Fixed wireless nodes • PLC wireless access point (hybrid system)	• Network size (number of radios) • Wireless range	• Smart Antenna • Spread Spectrum • Channel Coding • Elec. Status
UWB	—	—	• To be determined based on outcome of FCC final rulings	• Current FCC restrictions	• Smart Antenna • Spread Spectrum • Channel Coding • Elec. Status

Technology	Existing Structure		Portable Add-on Equipment for System Enhancement	Limitations	Potentially Applicable Enhancing Technologies
	Built-in Infrastructure Required	Modifications Required			
PLC	• Uses existing ac power lines	—	• Range extender	• Range	• Smart Antenna • Spread Spectrum • Channel Coding • Elec. Status
MF	• Uses existing telephone • Uses existing ac power lines	—	• Undetermined	• Limited research on in-building propagation	• Spread Spectrum • Channel Coding • Elec. Status
BDA	• Cable, antennas	• Installation of cable, antennas if not built-in	—	• Pre-installation required • Frequency must match that of fire department	• Smart Antenna • Elec. Status
VLF	—	—	—	• Narrow frequency band limits usefulness	• Channel Coding • Elec. Status
RF on HVAC	• HVAC ducts	• Modification to existing HVAC	—	• Pre-installation or modifications required • Duct size must accommodate/pass frequency used by fire department	• Elec. Status

STANDALONE TECHNOLOGIES

MANet

Mobile area networks could provide firefighters with voice and data communications as well as supporting radio location technology. MANets for commercial applications is a field of intensive research and product development.

In a MANet, each firefighter carries a networked radio. As soon as two radios are within range of each other they form a network over which voice and data can be sent and received. As more radios move with in range they automatically join, too. If two radios are out of range of each other but on the same network, the networked radios between them relay the voice and data from one radio to another until the destination is reached. National Institute of Standards and Technology (NIST) has demonstrated this networked radio approach to communication and location on its first responder test bed. [**189**] A MANet can also include the use of wireless access points to a local area network (LAN) such as the HomePlug LAN (described below) to provide range extension into especially difficult coverage areas.

There are no regulatory issues with MANet but there are technical areas to be addressed. Currently, quality of service measures (e.g., the time delay from source to destination) and communications capacity degrade rapidly as the network adds radios. Extensive research is needed to improve routing protocols to address this and other issues.

Ultra Wide Band (UWB) Communications

UWB technology addresses in-building communications and locations needs. UWB can propagate better through materials and is degraded less by multipath than narrower band communications techniques.

This is a field of intensive research because of its in-building propagation characteristics and the high data rates that can be achieved. For communications, the majority of the research is directed at using UWB as the wireless link technology in LANs such as MANets.

The major barrier to this field is regulatory. The FCC has restricted both the band and transmitted power level resulting in severely reduced range and data transmission rates. The fire service should evaluate this technology, develop requirements, and encourage the FCC to implement rules so that fire services needs can be met. Despite this barrier, UWB holds much promise.

Power Line Communications (PLC)

A PLC communication system could provide improved firefighter communications wherever power lines run. There are two types of PLC, HomePlug and Access PLC. Both use standard ac power lines for propagating high frequency (HF) signals. HomePlug is the only power line LAN standard used within structures and products are widely available in stores. There are several proprietary Access PLC standards in the trial stage competing to deliver Internet service to end-users.

Standard HomePlug devices provide the ability to quickly setup a fully functional LAN. One available device of particular interest is a wireless-access-point-to-HomePlug interface. In this type of application, the HomePlug network is used for range extension of a wireless network. Firefighters equipped with a MANet communication system could carry these devices into a building with them and plug them into ac receptacles as needed to provide coverage in areas where they are out of range of the MANet. Their radio communications would be carried by the ac lines to other identical wireless-to-HomePlug interfaces plugged into other areas of the building and where firefighter MANet radios would be able to receive and relay the communications.

HomePlug devices do not have regulatory issues, as HomePlug is an accepted standard. There are technical issues, however. The ability of these devices to provide range extension for a wireless communications system such as a MANet needs further study. Studies to-date have been technology demonstrations for home use. These have found that a percentage of the ac receptacles do not support adequate network performance.

This effort needs to be expanded to cover additional structure types and their ac distribution schemes.

Alternative Frequencies (MF and VLF)

These frequencies are not currently used for firefighter communications but are used in underground mines for voice communications because of their unique propagation characteristics.

The MF band has been used in underground mines because of its ability to couple with conductors in tunnels and propagate for several miles on the conductors. In this system a base station takes exterior communications (e.g., a phone system), converts it to an MF radio frequency signal and couples it onto a conductor such as the ac power lines. Miners use portable radios and wear portable antennas built into a vest or worn bandolier style to receive and send voice communications.

Frequencies in the VLF band can propagate through hundreds of feet of earth. The entire VHF band is about the same bandwidth as a single trunk radio channel, which severely limits the capacity for voice and data communications. One practical use of VLF is as a one-way emergency evacuation pager to miners. The transmitter and antenna can be located on the surface and still reach miners equipped with portable emergency receivers.

VLF based systems have been used to locate miners below ground as well but the inherent lack of location accuracy may not provide performance sufficient for firefighter applications.

These technologies' applicability to firefighter communications and location need to be tested as their use has been limited to underground mines where the propagation is heavily dependent on the tunnel characteristics. In addition, commercial developments in this area appear to be at a very low level as the bulk of the research and testing was performed over 10 years ago. There may be spectrum regulatory issues as these bands are currently allocated for other uses.

TECHNOLOGIES USING BUILDING INFRASTRUCTURE

Bi-directional Amplifiers (BDA)

BDAs provide improved in-building communications. This approach installs cable and interior antennas for distributing radio signal throughout a building to provide extended in-building coverage. They are difficult to retrofit into existing buildings, costly to retrofit or include in new construction, and require special RF engineering expertise when designing each installation, as each installation will be unique. BDAs also require periodic maintenance to ensure the system continues to function as designed.

These systems have been installed in a large number of buildings and face no technical or regulatory issues. Use of them as a standard firefighting tool has been resisted because of implementation costs. Local jurisdictions are reluctant to require them by code, as they must compete with other areas for business. A nationwide or regional approach should be investigated requiring these systems in new construction.

RF Distribution Using HVAC Ducts

This approach could provide better in-building communications. It takes advantage of existing heating and ventilation ducts as RF waveguides for distributing radio signal throughout a building. It would potentially provide a low cost method for distributing radio communications analogous to BDAs.

For this approach to work, the ventilation system must be modified to enable RF signals to bend around obstacles, such as fans and dampers, found in ducts. Also, room vents would need to be replaced with ones that would be RF-friendly. Very little research is being pursued in this area and has attracted little commercial interest as well. This technology should be monitored; if commercial interest develops it could provide a lower cost alternative to BDAs.

ENHANCING TECHNOLOGIES

The following four technologies can also be used to enhance the function of existing digital communications system regardless of the system architecture. All are being intensively researched and all should be considered for inclusion in firefighter communication systems. Smart antenna technology can be applied to both analog and digital systems.

Smart Antennas

Smart antennas are under intensive research for many communications applications, including use in wireless LANs such as MANets and commercial cellular systems. They promise to significantly extend the range and data rate that wireless links support. This may help address the data rate shortcomings in MANets as radios are added to the network. Smart antennas products have been announced for inclusion in wireless access points.

Channel Coding, Interleaving and Encryption

These techniques are present in almost all digital communications systems. Systems using these techniques function well indoor as they are less susceptible to conditions, such as multipath and interference, that cause errors. Firefighter radio systems cannot be retrofitted with these techniques and new radio systems would need to be developed.

Spread Spectrum Modulation

Spread spectrum modulations provide improved communications because they can mitigate reception problems caused by multipath and interference from narrow band radios. Again, firefighter radio systems cannot be retrofitted with this and new systems would need to be developed.

Electronic Status Systems

The newly announced electronic status systems automatically track firefighter status to address the difficulty faced by Incident Commanders in tracking personnel on the fireground. Radio channels are assigned to incident command sectors and the system tracks them and displays status on a laptop. Future enhancements will include the ability to poll individual firefighter radios to determine if they are in a coverage area. If they are out of coverage for too long a warning will be displayed. If the ability to determine radio location were integrated, it could further enhance firefighter safety.

Conclusion

Current firefighter communications systems were chosen more for mobility or availability of spectrum than for suitability to the job of providing robust, reliable communications into, from, and within structures. It is not surprising that they can fail to provide adequate communications in buildings, which are the most challenging of radio communication environments.

The technologies discussed in this report offer the possibility to significantly improve radio communications in large structures as well as in basement and other below grade areas. But it also appears that one technology alone will not be sufficient. Combining technologies together to make a hybrid system may be necessary. A MANet system provides the firefighter the mobility he needs; when coupled with a PLC or MF communications system, a MANet system may provide coverage even into difficult areas where radio waves cannot penetrate. Enhancing technologies can be integrated into this hybrid system to give even further improvements.

Many of the technologies considered in this report are undergoing commercial development at a fast pace. This promises to keep the underlying cost of the technology reasonable, although the special requirements of the fire service may impose additional costs. Commercial development should be encouraged, as the benefits of these technologies will improve fireground communications.

CHAPTER I: INTRODUCTION

One of the most significant problems facing firefighters within a structure on the fireground is the ability to communicate reliably between the firefighters themselves and between the firefighters and the command post or communications center. In an ideal world, firefighters would be able to communicate with one another and the command post at all times, regardless of where they are or what they are doing. However, this is not the case.

Over the past decade, incidents involving firefighter injuries and fatalities have demonstrated that, despite technological advances in two-way radio communications, important information is not always adequately communicated on the fireground or emergency incident scene. Also, the events of September 11, 2001, and other emergency situations in recent years have highlighted the need not only to improve firefighter radio communications, but also the communication systems available to law enforcement personnel, emergency management officials, and other public-safety responders. Equally important is the interoperability of all of these systems.

The continued incidence of firefighter fatalities where communications are cited as a contributing factor as well as the industry-wide lack of consensus on the appropriate frequencies to use in fireground communications have prompted NIOSH to more thoroughly investigate fire department communications and its problems.

Scope of Work

This study seeks to identify and address specific deficiencies in firefighter radio communications by researching the types of radio communication systems currently in use by the fire service and identifying what problems exist with them; identifying current technologies of interest to firefighter communications; identifying knowledge gaps regarding the effectiveness of such technologies; and finally, make recommending future research to improve firefighter radio communication and personnel location. In particular, this study focuses on communications problems caused by inadequate radio frequency (RF) signal propagation within a structure during firefighting operations and to and from the structure to the incident command post (ICP) or dispatch center.

The scope of work is described in more detail in Chapter II, “Methodology.”

Types of Radio Systems

Currently, most fire departments in the United States use conventional analog or digital mobile two-way radio technology operating in the 30–50-MHz band (VHF, low band), 150–160-MHz band (VHF, high band), 450–470-MHz band (UHF), and more recently the 800-MHz band. [**77,314**] Which type of system a fire department uses has both historical and technological reasons. Historically, the communication systems were first available in the lower bands. In terms of technology, communications systems have been chosen according to atmospheric propagation characteristics and to a lesser extent by structure propagation characteristics. For example, the lower bands propagate further through the air than do the higher. In a rural area, this is a plus as it allows coverage from a base over a much longer range, which keeps costs and complexity down. In an urban area the long range can be a minus as the radio environment has many more users within range and interference is a big problem.

Very high frequency (VHF) is the part of the radio spectrum from 30 to 300 MHz. VHF radio systems, either low band or high band, are simplex systems—messages are sent only one-way at a time. The low band provides relatively long-range coverage from base to mobile units but suffers from skip interference caused by distant low band signal skipping off the ionosphere and interfering with local radio transmissions. The high band also has problems with interference from mobiles up to 50 miles away and can only give reliable hand-held-to-hand-held communications for about ¾ of a mile unless the radio is elevated more than 5 feet above the ground. High-band VHF systems typically need to use repeaters to provide area coverage. Although, VHF has superior structure penetration in comparison to UHF [77], VHF's susceptibility to interference makes it a poor choice for urban use. Many rural systems use VHF radios because of their range, and because their relatively uncrowded RF environment does not cause unacceptable interference.

Ultra high frequency is the part of the spectrum from 300 to 3000 MHz. These ultra high frequency channels do not have the range of the low or high band frequencies of the VHF, and typically require the use of repeaters to have the same coverage as low or high band VHF frequencies [**84**]. Conversely, because of the shorter range and the lack of skip propagation, they do not suffer from the interference problems of the VHF bands.

VHF and UHF, except 800 MHz, are conventional radio systems. In a conventional system, a group of radios share one fixed channel or frequency. If that channel is in use by one user in the workgroup, service is not available to others.

The FCC has designated parts of the 800-MHz to 900-MHz radio frequency (RF) band as public safety radio frequencies for use in public safety trunking radio systems. Trunked systems, which are usually computerized, allow more efficient use of frequencies. In a trunked system a set of radio channels (a trunk) is assigned under computer control. When a firefighter transmits, a computer automatically assigns the firefighter to an open frequency. When the firefighter ends the transmission, the frequency is automatically made available to the next firefighter transmitting [**315**]. The operator does not have to manually select a frequency. Because these systems have multiple frequencies and they are only assigned while a radio is actively transmitting, they provide higher capacity than conventional VHF and UHF radios. This helps prevent radio system congestion. The high capacity of these systems and low interference from other users of the public safety trunking band make these systems appropriate for use in congested areas.

No band of frequencies is perfect; many frequencies work well. The selection of frequency is dependent on a variety of factors, including "frequency availability, area to be covered, type of terrain, number of radio units required, frequencies used by bordering fire [or public safety] districts, mutual-aid agreements, type of operation, and use of emergency medical radios."[**315**]

Communications from Inside a Structure to the Outside or Vice Versa

Fireground communication has significantly changed over the past decade with the proliferation of the portable radio. In the fire departments reviewed, each firefighter team of two will typically carry a small portable radio. In some fire departments each firefighter has their own radio. The increase in number of portable radios coupled with the multitude of communication systems has prompted many fire departments to reexamine their radio procedures, and develop new fireground communication protocols to aid in controlling radio traffic.

The focal point of all fireground communications is the command post. Typically, the command post will be positioned as close to the incident as safely possible to facilitate the communication process. The type of fire and the type of structure involved dictates the location of the command post. Structures such as high-rise buildings, tunnels, and sub-basements may disturb the effectiveness of portable radios and communications. In these situations, some fire departments may position the command post inside the structure to compensate for the portable radios' weak RF output. For example, on fires located on the upper levels of a high-rise structure the command post may be established several floors below the fire (as opposed to the street level) to help improve communication.

In the fire departments reviewed, each department had more than one tactical radio channel for fire operations. Typically, once the command post has been established, fire ground units are switched off of the main dispatch channel to a tactical fire ground channel. These channels usually have a restricted range that permits fire ground units to communicate independently of the main dispatch channel, and also prevent the bleedover of other radio traffic from other fire units operating in the vicinity.

Firefighters operate as a team consisting of two or more personnel. Each interior team can have one or more portable radios. To help control traffic, all radio communications with command post is normally made by the unit officer or the senior team leader. However, if fire conditions restrict visibility, team members may have to communicate with each other by radio, which can substantially increase radio traffic. Some departments restrict the use of individual portable radios to only emergency situations where firefighter may become separated or trapped.

The operation modes commonly used in fire department communication systems include simplex, duplex, and trunked.

The simplex mode requires both a transmitter and receiver at each end of the communications path. In simplex mode, only one end (i.e., the transmitter or the receiver) may operate at a time. It requires only one frequency. Only one firefighter may transmit a message on a portable radio while using a simplex channel, all others must receive.

During interior fire department operations, firefighters may switch to a simplex channel because their low-powered radios cannot transmit outside the building. Simplex channels do not require the use of repeaters or towers. Rather, the portable radios themselves act as the transmitter and receiver sites.

Duplex mode uses two frequencies that allow both ends to communicate simultaneously. Thus, one user may interrupt another to facilitate discussion. Repeaters may be used in a duplex system. Repeaters, typically located in a high place such as a mountaintop or tall building, receive a transmission from a radio (in the system) on one frequency and retransmits (or "repeats") on another. Repeaters can also be located in fire apparatus and command vehicles for use on particular incidents where communications are problematic. All radios with proximate distance will receive the transmission from the receiver. Repeaters are used to augment the range of the radio system.

Repeaters also allow a low-power portable radio to hear other radio messages (to, from, and within a structure) when obstructions may normally hinder communications. Sometimes, even in the presence of a repeater, obstructions are too great and will prevent a radio signal from being transmitted.

A trunked system, which may include a single user or different workgroups, uses a group of radio frequencies (a trunk). The system is dynamically controlled by a computer, which directs a transmission to an available channel or frequency.

Firefighter Radio Communications Problems

Communication problems encountered by firefighters (and others) can be broadly divided into two categories. First are mechanical or technical issues related to unsuitable equipment, radio malfunction, system design, inadequate system capacity (too much radio traffic), and failure due to extreme environmental conditions (e.g., fire, heat). Poor and mottled radio communications in large structures have also been a persistent problem. Another technical issue is interoperability, or the ability for various departments (e.g., fire, police, public works) to communicate with each other or another neighboring jurisdiction. The second category of problems relates to human factors.

In many instances, a variety of mechanical and technical issues such as RF attenuation, fading, and building construction can prevent the system from maintaining sufficient link quality for reliable communications. In large multistory structures, for example, the frequency may bounce of the walls and windows with reflective coverings, or simply be absorbed from the construction of the building. Some of these cases involve situations where a firefighter is in danger and most in need of communications. As a result, this lack of reliable communication could severely compromise the effectiveness, the safety, and even the life of the first responder.

Human factor include radio discipline, training, tactical decisionmaking as well as others. These factors combine with technical and equipment issues to adversely affect firefighter radio communications. As such, these factors are considered as a component of the overall analysis.

One of the most interesting comments about radio communications noted during this research is: "Our [the fire service] radio systems aren't failing, but rather we can't get the signal throughout buildings with 100 percent accuracy . . . this is affected by building construction, windows, elevator shafts, the output strength of the system, and the [strategic design and implementation of infrastructure such as the] presence of repeaters."[1]

Organization for the Report

The remainder of this report is divided into five major sections, each addressing one aspect of the study. The first section, Chapter II, reviews the study research methodology. The second section, Chapter III, discusses the overall firefighter communication problems, both technical issues and human factors. It also presents an overview of these communication issues as well as a review of communications issues that affect fire departments everyday. The third section, Chapter IV, examines the communication problems inherent in structures, and the risk to firefighters. The fourth section, Chapter V, discusses the results of the research and includes descriptions of available technologies of interest, their current applications, potential applications, limitations, and areas needing further investigation.

The report has two appendices. Appendix A is a tabulation of prioritized project issues, and Appendix B details the communications problems of 24 jurisdictions, both large and small. A Glossary of Terms and Abbreviation follows the appendices. The report concludes with a Master Reference List containing more than 350 citations used in the preparation of this report.

[1] Telephone conversation with Deputy Chief Jeff Coffman, Fairfax (VA) County Fire and Rescue Department.

CHAPTER II: METHODOLOGY

The project was divided into two primary tasks: to identify fire service communication problems and solutions and to research and analyze the potential solutions to the technical RF issues involved in resolving and improving these communications problems. From the outset, the project was further refined to focus on communications problems within as well as to and from structures, to include high-rise buildings, tunnels, basements, underground parking garages, and subway systems.

Determination of Critical Areas of Interest

To begin the project, the team members compiled a comprehensive set of communications issues that affect radio communications in the fire service from several sources – an initial literature survey, knowledge of the project team members, and discussions with fire service leaders, NIOSH project team, engineers, and others. Team members refined this comprehensive set of issues with NIOSH project personnel to identify critical issues that could be addressed by improvements in radio communications. A prioritized list of communication and personnel location problem areas was developed. In general, the primary focus was clarified to be the identification, status, and research recommendations for technologies that could improve communications or provide firefighter location within structures. The list of the high priority topics is shown in Table 3 below. The full list of ranked topics is attached as Appendix A with '10' being a highly ranked problem and '1' the lowest.

TABLE 3: PRIORITY TECHNICAL AREAS AND RELATED TOPICS ADDRESSED IN STUDY

Ranking	Area	Example Issues
10	Accountability (Integrating Personal Accountability Systems (PAS) with Communications)	• Integrating PAS with communications • Electronic accountability • Automatic vehicle location • Electronic command boards
10	Communication Planning and Coordination	• Through building (into/out of) • Underground • In building
10	Monitoring Firefighter Welfare and Location On-Scene	• Role/responsibility of dispatchers. • Use of field communications units and communications coordinators • Remote monitoring • Vital signs • Location
10	Reliability	• Line-of-sight limitations • Underground (subways, parking garages) • Confined space rescue • Communication into and out of buildings (especially high rises) • Intermittence • Communication coverage/dead spots

Ranking	Area	Example Issues
10	Interference	• Building construction and materials (such as concrete, metal, and Lexan) • Radio propagation through fire, heat, and smoke • Cell phone towers (e.g., Nextel) • Terrain
10	Unsuitable Equipment	• Frequency band unsuitable for structure/ground penetration

Information on and about grants to pursue these technology areas was originally ranked as one of the priority issues. Because grants are not within the scope of the technical nature of this project, this topic was not pursued. Grants, however, are available through the United States Fire Administration (USFA), National Institute of Standards and Technology (NIST), and other sources as well. The USFA, through its Assistance to Firefighters Grant Program, has awarded funds to many fire departments to purchase communications systems and other equipment. Money is also available from NIST for research and development.

Literature Review

Based on this prioritized set of topics, the study team conducted a comprehensive literature review to research the radio communication technology in use by firefighters, what problems exist with communications, and on relevant research/evaluations of existing or proposed technology. The team searched a variety of bibliographic databases including the following:

Engineering Index – The Engineering Index contains abstracted information from the worldwide significant engineering and technological literature. It covers approximately 4,100 journals and selected government reports and books from 1970 to the present. Over 480,000 records of significant published proceedings of engineering and technical information are also included.

INSPEC – INSPEC is a database containing bibliographic citations to items in *Physics Abstracts*, *Electrical and Electronic Abstracts*, and *Computing and Control Abstracts*. Over 4,100 journals and serials are scanned from 1969 to the present. Included are papers, journal articles, conference proceedings, books, reports, and dissertations.

PubMed – PubMed is the National Library of Medicine's (NLM) search service that provides access to over 11 million citations in MEDLINE, PreMEDLINE, and other related sources journals. MEDLINE is NLM's premier bibliographic database and contains over 12 million citations from the mid 1960s to the present. PreMEDLINE is the in-process database for MEDLINE, containing details of very recently published articles. The journals primarily fall within the general science and chemistry field. MEDLINE contains bibliographic citations and author abstracts from more than 4,600 biomedical journals published in the United States and 70 other countries.

Nerac –Nerac began operating in 1966 as the New England Research Application Center, an experimental collaboration between the University of Connecticut and the National Aeronautics and Space Administration (NASA). Nerac provides peer-reviewed literature from a collection of over 250 million abstracts, citations and full-text articles. Nerac locates published articles from international resources to bring information that is typically unavailable through Web-based search engines. Its databases include information on journal articles, patents, conference papers, theses, business and financial reports, manuscripts, and government regulations. Nerac searches can be applied to 128 separate databases of which 57 are in the engineering fields. The databases that were accessed most heavily for this project were:

- Aerospace Database
- DTIC – Defense Technical Information
- Inspec – Electronics and Physics
- Dissertation Abstracts
- Inside Conferences
- Conference Papers Index
- U.S. Patent Applications

CiteSeer (Research Index) – CiteSeer is a scientific literature digital library that indexes Postscript and PDF research articles on the Web. Developed by NEC (formerly Nippon Electric Company), it allows the user to quickly track how research has been used and what recent developments have occurred in the research area. The automated indexing system not only indexes research articles by crawling journal websites on a regular basis, but will also index each article's citations, which can be viewed in the context of the article. This context enables the reader to judge the links between studies and the citations noted in the research.

National Technical Information Service(NTIS) – NTIS is a database of the U.S. government agencies containing only unclassified literature, some state and local governments, and some non-U.S. governments. Coverage is from 1964 to the present; included are reports, bibliographies, conferences, symposia, government documents, journal articles, patents, standards, and translations.

Firedoc – Database of the National Institute of Standards and Technology’s Building and Fire Research Laboratory (BFRL). It contains publications from the BFRL staff, its contractors and grantees from the early 20th century. Over 60,000 bibliographic records and indexing are in English from the BFRL staff and for fire research and fire engineering organizations and fire departments worldwide regardless of language. Reports, journal articles, conference proceedings, contractor and grantee reports, and audio-visual materials are included.

USFA/FEMA Online Catalog – This online catalogue is a database of the U.S. Fire Administration/ Federal Emergency Management Agency. It contains bibliographic citations (and abstracts Executive Management Institute's papers) to over 100,000 books, reports, periodicals, and audio-visual materials on their collection.

InfoTrac OneFile – InfoTrac OneFile provides access to periodical and news information on a diverse set of topics, including humanities, education, business, science, current events, art, politics, economics, social science, law, health care, computers, technology, environmental issues, and general interest topics. InfoTrac OneFile has access to nearly 32 million articles in a wide variety of periodicals.

In addition, the team searched for information from other federal agencies, such as the National Aeronautical and Space Administration and the Federal Communications Commission. Private industry sources were also explored, from the National Fire Protection Association to the Association of Public-Safety Communications Professionals, among others. The Internet was used to access current trends and products.

The results of the literature review included a variety of published materials, including technical reports, trade journals, academic research papers, CD-ROM collections, government reports, open-source material available on the Internet, media reports, international studies/reports, and manufacturer/vendor literature.

Fire Department Communication Issues Review

Once the technical literature review was well underway, the study team gathered and reviewed fire service communications literature and studies. The information was gathered from a variety of sources: much of the information comes from fire department management studies previously undertaken by TriData Corporation. Some information comes from individual fire department annual reports, websites, or other fire department literature. Wherever possible, the information from these studies was verified with the fire department to ensure that the most current data was reflected in this report. The reviews focused on actual communications problems experienced by various jurisdictions and the solutions implemented to mitigate them.

The technical literature review yielded a number of promising technology areas. During the course of this research, the study team contacted experts in these areas to determine whether the new products and research had potential to improve firefighter communications. These contacts were conducted primarily by telephone and email.

Knowledge Gaps Analysis

Based on the information collected through the literature search and discussions, a review was conducted of the available knowledge and research related to radio communication systems. We identified the gaps between what current technology yields for firefighter radio communication and what would be necessary to address the firefighter location issues and more effective communications within structures. We also determined what technologies and solutions are available bridge these gaps; and addressed future technologies or products that could improve overall firefighter communication and safety.

The analysis approached the knowledge gap problem from three angles. First, we examined the gap between the current technical knowledge of the problems and current proposed solutions. Second, we assessed the gap between available published material and the material actually needed to fully address the issue. Finally, we considered the gap between the available technology and the implementation of that technology in the fire service.

Recommendations

The final step in the study process was to develop a series of recommendations for areas of future research to improve firefighter communications. Where possible, specific vendors, agencies, and other resources are identified as avenues to complete this research.

CHAPTER III: FIREFIGHTER COMMUNICATION ISSUES

Communication problems commonly encountered by firefighters (and others) can be broadly divided into two categories. First are mechanical or technical issues related to unsuitable equipment, system design, inadequate system capacity (too much radio traffic), and building construction, among others.

The second category includes human factors such as radio discipline, training, and tactical decisionmaking. These factors, while not technical issues themselves, adversely affect firefighter radio communications, especially when combined with technical and equipment issues.

This chapter presents an overview of these communication issues as well as a review of communications issues that affect fire departments every day.

Technical Issues

Fire departments consistently have problems maintaining effective communications while operating in large structures, such as high-rise office buildings and apartments, and warehouses. Similar issues exist in structures with a large number of windows (or areas of glass) with reflective coatings. Communications from areas below grade (e.g., basements, parking garages, subway systems, tunnels) tend to be uneven. For the typical home, communications are generally not a problem. The technical issues associated with the physical structures themselves (building materials, height, etc.) are discussed further in Chapter IV.

Below is a discussion of the technical issues that are commonly associated with fire department radio communication difficulties.

EQUIPMENT

In general, the most common communication problem encountered by firefighters is the inability to effectively communicate while wearing self-contained breathing apparatus (SCBA). In addition, it is difficult to operate most portable radios while wearing full personal protective gear (PPE). Thick fire suppression gloves make it difficult to turn knobs or push buttons, and low-light and smoke conditions coupled with wearing an SCBA facepiece make it hard to see the LCD display on a radio (if so equipped).

Another common problem is the equipment's tolerance to hazardous environmental conditions, such as high heat, prolonged exposure to water, and rough handling. While radios are water resistant, not all models are waterproof. This is more of a problem with older radios, however, as newer models are more water resistant if not completely waterproof.

Many radio systems are highly dependent on computer technology. In the event such technology fails (e.g., the trunking software becomes inoperable), the entire radio system can be disabled.[2] To prevent complete failure of the radio communication system, most jurisdictions employ backup analog frequencies to maintain critical communications (e.g., dispatch and contact with units). Reliability and sustainability are key components of any sophisticated system.

The usefulness of a portable radio is dependent on the life of its battery. Some older radios require batteries to be "conditioned" or otherwise use special chargers for optimal battery life. This requires users to be especially diligent about maintaining radios and their batteries, which can be challenging for departments already busy with emergency response and apparatus maintenance.

SYSTEM DESIGN

Perhaps one of the most critical technical issues related to radio communications is the design of the system itself. Whether a department uses low band, high band, analog, or digital technology, an adequately funded, carefully thought out, strategically designed system (i.e., the number and placement of tower sites and repeaters) will perform better than one that was not carefully planned.

The lack of frequencies available to public safety agencies has made it difficult for some jurisdictions to modernize their radio communications systems. Public safety departments are limited to VHF low band, VHF high band, UHF 450 MHz, and UHF 800 and 900 MHz. Instead of transitioning to a completely new system, many jurisdictions are exploring the possibility of applying new technology to enhance their existing system's capability with only a modest expenditure of fire department budget.

There are common design problems for most systems. An inadequate number of tower sites and repeaters typically result in "dead spots" – areas where radio communications are difficult or impossible. Buildings and terrain, among other factors, can cause dead spots. Similarly, a system might be designed with too little signal output to reach all areas of the jurisdiction (in some areas, for example, the radio system output is limited due to proximity to an airport or the Canadian or Mexican borders).

As discussed later in this chapter, fire departments cannot always separate dispatch and tactical operations channels. This is a critical function, as the combination of dispatch and incident operations can overwhelm a single radio channel, causing critical messages to go unheard. Some experts also argue that large-scale incidents (e.g., high-rise fires) should

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[2] In a trunked radio network or system, a large number of workgroups (or users) share fewer channels because the trunking equipment dynamically allocates an available channel when users key their radio. A computer manages the system. When a user (e.g., firefighter) has a message to transmit, the computer assigns an available trunk. "The advantage of this type of system is that it uses a group of available frequencies more efficiently by utilizing the capabilities of the computer to manage the radio traffic on each frequency. Thus, more radio traffic can be handled on the available frequencies, without causing congestion and interference." [**314**]

use multiple tactical channels to separate key functions, such as fire attack, search, emergency medical services, command, etc.

SYSTEM CAPACITY

In general, fire departments throughout the country are responding to a higher number of calls for service than ever before and call volume will continue to rise. The majority of these calls are for EMS, which is a national trend. While EMS calls do not typically require a tactical channel, the associated radio traffic (e.g., dispatch, response, ER consults) may add to the system traffic. A dramatic increase in call volume and increased frequency of use may cause the system to reach capacity. As a result, existing communications may lack the capacity to handle the associated rise in radio traffic.

A large-scale event such as natural or other disaster (i.e., terrorist event) is also likely to dramatically increase system traffic. In such cases, multiple city agencies or departments are likely to be at the scene of the incident, each using its respective communication system, possibly causing the radio system to reach capacity.

Trunked systems provide more capacity than conventional VHF and UHF radio systems because a computer assigns a frequency only while a firefighter is actively transmitting, and then automatically takes it back when the transmission ends so the signal is immediately available for another transmission.

INTERIOR (STRUCTURE) COMMUNICATIONS

It is critical for firefighters to communicate with one another within a structure and with units operating outside the structure, regardless of the building construction. The inability to communicate from buildings, below grade, basements, garages, tunnels, etc., is a persistent problem in the fire service.

The construction of a structure can contribute to communications problems. Residential buildings are typically constructed of wood and other materials easily penetrable by radio waves. Commercial structures, however, are typically built with large amounts of steel and concrete that, to varying degrees, act as barriers to radio frequency waves. In addition, some types of glass and other window materials used in commercial construction inhibit radio frequencies. This topic is discussed in depth in Chapter IV.

High-rise structures, warehouses, and underground structures such as tunnels and basements pose their own challenges to radio communications. In addition to the construction materials used to build them, the height of such structures can interfere with line-of-sight (LOS) access to repeaters and radio towers.

Following the September 11, 2001, terrorist attacks, the Fire Department of New York (FDNY) contracted with McKinsey and Company to review its response and preparedness for future events. Based on interviews with firefighters, McKinsey reported that communication failures occur on a regular basis when transmitting from the inside to outside or vice versa from a high-rise building, tunnel, or subway system. Of the over

2,000 high-rise buildings in New York City, the FDNY feels that only a fraction allow reliable communications. [**51**]

After-incident reviews of the World Trade Center collapse indicate that inadequate communications prevented personnel from receiving critical information about the impending collapse of the Towers. The reason cited was that FDNY portable radios do not work well in high-rise buildings and the signals from the radios were rebroadcast by a repeater system. Therefore, when critical information was relayed, it was sporadic or not fully received.

McKinsey and Company notes that the communication failures can be corrected by deploying repeating infrastructure that "receives, amplifies, and retransmits radio communication signals to improve coverage." The report observed that portable repeaters "may help mitigate in-building communication difficulties, but do not provide full coverage for high-rises," and suggests that stationary repeating infrastructure is preferred, especially if it is "designed, installed and maintained properly." [**51**]

With an estimated cost of $0.30–$0.60 per square foot of high-rise space, McKinsey and Company estimates that FDNY would have to spend upwards of $250 million to install permanent repeater systems to ensure radio communications in the city's high-rise structures. In the case of tunnels, McKinsey recommends that FDNY participate in the Police Radio System, which is funded by the Metropolitan Transportation Authority. The Police Radio System uses UHF radios to maintain two-way voice communication. Particularly with the vulnerability of a limited security subway system to a terrorist attack, FDNY and other fire departments with subway systems in their districts should ensure that communication systems are fully operational in these structures.

POOR RECEPTION

Inadequate radio reception is the result of many factors. Most notable among these factors are low power, interference, and the terrain-and-built environment.

There is a direct relationship between RF power output and transmitting range. The higher the RF output, the greater the transmitting ranges, and vice versa. Portable radios have a low RF output and, therefore, have a short operating range. On average, the RF output of portable radio range from 1 to 7 watts. [**314**] In comparison, mobile radios typically have an RF power output 20–100 watts. [**314**] Because mobile radios are not portable, they cannot provide on-scene communications or be carried into a large structure. As a result, firefighters must carry low-powered portable radios, which may not work very well in large structures.

Atmospheric interference is uncontrollable. This natural occurrence results from solar disturbances on the surface of the Sun. These solar disturbances, also known as "solar flares," emit large volumes of electromagnetic radiation and highly energized particles, which can affect satellite and radio communications on Earth. The highly energized charged particles pass through the ionosphere traveling at the speed of light and can affect radio signals over the entire frequency spectrum.

Electronic interference is also common. Many public safety radio systems often suffer destructive interference from a variety of sources, including commercial 800-MHz trunking antenna sites (Nextel, for example), interference with other public safety radio systems (e.g., neighboring jurisdictions), or other electronic devices.

The environment – both topographic factors and the built-in environment (e.g., high-rise buildings) – is yet another cause of poor reception and solutions exist to help correct these reception problems. In some areas, additional antenna sites have reduced (or eliminated) interference caused by environmental factors.

INTEROPERABILITY

Radio communications interoperability allows various departments (e.g., fire, police, public works) to communicate with each other or another neighboring jurisdiction. The objective is for these departments to exchange information when necessary (e.g., mutual-aid call, mass casualty incident, special event).

Throughout the country, adjacent jurisdictions or even agencies in the same jurisdiction use different radio communication systems. For example, while one county may use high-band frequencies (154.115–159.21 MHz), its neighboring jurisdictions might use an 800-MHz trunked system. Or, a city's police department could use an 800-MHz trunked system while the fire department uses a high-band system.

Interoperability is not only critical in the case of a major emergency incident or disaster, but also important for the everyday types of calls where two or more departments are involved.

While a significant problem in fire service communications, interoperability is outside the scope of this report and is not addressed in detail.

DIGITAL VS. ANALOG

Modern communication systems are evolving from analog to digital technologies. Digital systems offer better performance over a broader range of conditions, much greater flexibility, and more efficiency than analog at a lower cost. As with most alternatives, tradeoffs must be considered. Rarely does one find that all the pluses are on one side and that is the case with analog and digital communications.

Performance

The human ear corrects errors in analog communications systems. It can decode a wide range of hissing, crackling, volume changes, and other variations. As the signal to noise ratio (SNR) degrades, there comes a point where the transmission cannot be understood. But with digital communications, other error-correcting methods must be used. Digital communications allows for error-correcting codes that provide clear transmission over a much wider range of SNR than analog. However, at some point as the SNR drops, it falls so low that the digital system can no longer correct errors. When this happens, the signal quality varies from perfect to gone. So, while digital schemes are capable of error-free transmission while analog ones are not, it is not uncommon to find radio users who prefer to let their ear decide when the transmission is indecipherable rather than have the signal just go away.

Flexibility

Digital communication systems can transmit analog signals obtained by analog-to-digital conversion, plus information such as computer data. Any signal that can be sent by analog means can be sent digitally. But an analog system cannot send everything that a digital system can. Video can be sent by analog means (standard television), but better performance is obtained using digital (HDTV). In addition to the ability to transmit a wider variety of signals than analog systems, digital communications can be organized into area-wide communications systems such as computer networks. These digital networks can be local, wide area, or even global and provide efficient and flexible data transmission not remotely feasible using analog means.

Security

Digital communications can be encrypted to provide robust security while analog cannot be protected nearly as well.

Efficiency

With digital communications, signal structure can achieve a much more efficient communication system via digital compression techniques. Digital communications are efficient enough to send more information per user to allow more users to occupy a given number of radio spectrum or channels. In analog communication, the only parameters of interest are message bandwidth and amplitude.

Consequently, with the increased speed of digital computers, the development of increasingly efficient digital communications algorithms, and the ability to interconnect computers to form a communications network, digital communication is now the choice for many situations.

Human Factors

Even with the most technologically advanced radio communication system, the success and failure of radio communications depend on the person who transmits the radio message as well as the one to whom the message is transmitted. For example, location of the microphone in relation to the mouth and SCBA when transmitting can be important with some radio systems. The clarity with which the transmitting person speaks, coupled with the volume of the transmission, will drive the audibility of the message at the receiving end. It is also incumbent on firefighters to know when to transmit over the radio and when not to transmit a message.

Message Transmission

Well thought-out, clear, and concise messages are important characteristics for firefighters to employ during their radio transmissions. On the fire scene, when firefighters are excited or are panicked, radio transmissions can be loud and uncontrolled. Messages of this nature are difficult to understand. Discipline requires firefighters to exercise discretion in messages transmitted over the radio. Noncritical messages increase the radio traffic and may prevent emergency messages, such as a Mayday event or impending building collapse, from being transmitted.

Over the years, radio codes and other phonetic techniques have been developed to make communications understandable, both for the sake of clarity and to compensate for poor radio links. These include the widely known phonetic alphabet (Alpha, Bravo, …, Yankee, Zulu). Such alphabets, used for spelling things out over voice links, are variously known as phonetic radio spelling telephone alphabets and analogy alphabets. In addition, codes are commonly used by police and other agencies to provide succinct communication. These may be “10:4” or other numeric based messages that in some cases describe a response or situation. In spite of these techniques, clear and understandable radio communication is still a common problem. Firefighters must learn any terminology used in their jurisdiction.

To counter problems with distortion and inaudible radio communications while wearing SCBA, some equipment manufacturers have designed integrated microphone and speaker systems into SCBA. Depending on the manufacturer, some of these systems use a bone microphone worn by the firefighter or a microphone integrated into the SCBA facepiece. Speakers are often a modified headset that fits in the firefighter’s ear, under their SCBA face piece and other protective gear. Most include a large, easy to operate push-to-talk button for use while wearing firefighting gloves. These systems increase the clarity of radio transmissions, reduce the amount of feedback from radios being too close to one another, and increase the likelihood that the transmission will be heard and understood.

Difficulty Operating Radios

As mentioned previously, the use of full PPE and SCBA makes it difficult to use a portable radio effectively. While the push-to-talk button is generally easy to use with gloves, the knobs and other buttons can be much more difficult. To overcome this, some departments are programming their radios so that the first and last position on the channel selector will automatically direct the firefighter to a channel monitored by the dispatch center. In the event of an emergency, the firefighter can turn the dial all the way in either direction and reach someone to alert them of the emergency.

Inadequate Training

Though firefighters receive hundreds of hours of training on emergency response, radio communications do not typically receive the same amount of attention. As such, firefighters may not be aware of proper radio usage. Examples include how to use the radio in general, how to use the radio while wearing SCBA, and how radio communications are affected by a Mayday event.

FIRE SERVICE CULTURE

Firefighters are, by their nature, problem solvers and independent. It is difficult to convince firefighters that they need to call for help quickly in the event that they become lost, trapped, or incapacitated. Waiting to call for help delays rescue efforts. And when a firefighter's Mayday calls are not initially heard, rescue efforts can be delayed even longer.

Applicable Standards and Regulations

Standards have been developed to address communications systems, but, by and large, such standards are mute on identifying the best system for fire service communications. Thus each jurisdiction has the challenge of designing and building a radio communication system that meets its current and anticipated future needs.

NFPA

The National Fire Protection Association (NFPA) is a national nonprofit organization that develops consensus based codes and standards for the fire service. The NFPA has developed NFPA Standard 1221, *Standard for the Installation, Maintenance, and Use of Emergency Services Communications Systems*, 2002 Edition. This standard does not make specific recommendations on the types of radio system or frequency ranges that should be used by fire departments for emergency incident communications. Rather, it addresses construction, layout, staffing, and emergency backup components of the communication center.

The nineteenth edition of the NFPA's *Fire Protection Handbook* references radio frequency selection, but only shows that fire departments use VHF low band, VHF high band, UHF 450 MHz, and UHF 800 MHz and 900 MHz. It does state that, "each band of frequencies has its advantages and disadvantages, and the selection of a particular band will depend on factors such as frequency availability, area to be covered, type of terrain, number of radio units required, frequencies used by bordering fire districts, mutual aid agreements, type of operation, and use of emergency medical radios."[**314**] The handbook also describes Simplex, Two-Frequency Half Duplex, Two-Frequency Full Duplex, Two-Frequency Repeater Systems, Trunked Systems, Tone-Coded Squelch, and Radio Paging Systems, but does not take a stance or recommend one type of system or frequency over another.

FCC

The Federal Communications Commission (FCC) is an independent United States government agency, directly responsible to Congress. The FCC was established by the Communications Act of 1934 and is charged with regulating interstate and international communications by radio, television, wire, satellite and cable. The FCC's jurisdiction covers the 50 states, the District of Columbia, and U.S. possessions.

Recent FCC activity of interest to the firefighting community includes:

- Permitted use of UWB devices in restricted bands and restricted transmit power.
- Removal of 50 MHz of government frequency allocation from 4840–4990 GHz with reallocation to public safety use. This band permits broadband services in support of public safety.
- Allocation of 764–776 MHz and 794–806 MHz for public safety use.
- Development and promotion of broadband services to compete with local broadband service from cable and telephone companies. As part of this effort, the FCC strongly supports development of Access PLC, which uses the medium voltage power grid to deliver broadband service to homes and offices.

PSWAC

Congress empowered the Public Safety Wireless Advisory Committee (PSWAC) in June 1995 to address issues relating to spectrum needs and uses for the public safety community. The PSWAC identified an immediate need for 2.5 MHz more of spectrum, and a longer term need for an additional 25 MHz of spectrum for public safety use. PSWAC found that 70 MHz more of spectrum must be allocated if the public safety agencies and emergency responders were to use modern technologies, many of which require additional spectrum.

Experiences From the Field

This section summarizes the communications problems — mechanical and technical issues, as well as human factors — that are commonly encountered by jurisdictions throughout the country and the solutions implemented to mitigate them. Below are highlights of the actual communications problems experienced by these jurisdictions; a more comprehensive writeup is found in Appendix B.

The departments reviewed were mostly all-career fire departments, large and small, in mostly urban or suburban areas as the information on these departments was more readily available. A small group of volunteer departments and jurisdictions in rural areas was also reviewed. In some instances, urban fire departments also provide fire or EMS services to rural areas.

In all, information from 24 fire departments is included in this report. Of these, 18 are all-career fire departments, 5 are combination, and 1 is an all-volunteer fire department. Table 4 summarizes the departments reviewed.

The jurisdictions ranged in population from a high of 3.7 million in Los Angeles to a low of 3,700 in Gettysburg, OH. The service land areas also varied widely (as does the physical characteristics — terrain and topography — of each area). Land area protected, as measured in square miles, ranged from 15 square miles in Springfield, NJ to 8,000 square miles in Clark County, NV.

Communication and radio system priorities differed somewhat in urban and rural departments. In urban settings, fire departments contended with a larger variety of structures such as high-rise buildings, multilevel residential structures, basements, tunnels, and underground transportation systems (e.g., subways). The rural areas, typically residential in nature, had fewer large buildings and generally no underground transportation systems.

TABLE 4: SUMMARY OF FIRE DEPARTMENTS REVIEWED

Jurisdiction	Resident Population[3]	Land Coverage area (square miles)	Land Area	Fire Department Type
Austin, TX	656,562	252	Urban	Career
Bellingham, WA	67,171	32	Urban/Suburban	Career
Boston, MA	589,141	48	Urban	Career
Boulder, CO Rural Fire Department	18,000	25	Suburban/Rural	Combination
Brighton, CO	20,905	17	Suburban/Rural	Combination
Charlotte, NC	540,828	242	Urban	Career
Chicago, IL	2,896,016	227	Urban	Career
Clark County, NV	1,375,675	8,000	Urban/Rural	Combination
Dallas, TX	1,188,580	385	Urban	Career
Detroit, MI	951,270	139	Urban	Career
Everett, WA	91,488	48	Urban/Suburban	Career
Fairfax County, VA	969,749	395	Urban/Suburban	Combination
Gettysburg, OH	3,700	60	Rural	Volunteer
Los Angeles, CA	3,694,820	469	Urban	Career
Milwaukee, WI	596,974	96	Urban	Career
Phoenix, AZ	1,321,045	475	Urban	Career
Pittsburgh, PA	334,563	56	Urban	Career
Portland, OR	529,121	134	Urban	Career
San Antonio, TX	1,144,646	412	Urban	Career
San Diego, CA	1,223,400	324	Urban	Career
San Francisco, CA	776,773	49	Urban	Career
Schaumburg, IL	75,386	19	Suburban	Career
Springfield, NJ	14,429	15	Suburban	Combination
Wichita, KS	344,284	136	Urban	Career

In addition, urban systems experienced higher service volumes and increased radio traffic. Urban areas had a higher propensity for radio congestion. Fire departments in urban areas were mostly career, sometimes supplemented with volunteers, whereas rural systems have more volunteer providers.

[3] Data from U.S. Census 2000 is used for consistency and comparison. Data may not agree with that reported by the jurisdiction.

Topography and terrain in both urban and rural areas varied widely. Typically, rural systems covered larger land areas that are more spread out and not as densely populated. Natural elements such as mountains, hills, and other potential interfering terrain were present in both urban and rural systems, depending on the area.

More often than not, the urban departments have the resources to provide a communications system with the necessary hardware that meets the needs of the area. The urban areas had a greater population and tax base. In many departments, the fire department operating budget comes directly from property taxes. Properties in urban areas generally have a higher assessed valuation than an equal property in a rural area, and therefore will raise more tax dollars.

Table 5 summarizes radio communications issues commonly experienced by the fire departments reviewed for this study.

TABLE 5: SUMMARY OF FIRE DEPARTMENT RADIO COMMUNICATION ISSUES

Topic	Area	Issue
Poor Reception	Physical environment	• Canadian & Mexican borders • Topography and terrain
	Interference	• Neighboring jurisdictions • Wireless communications
Interior Communications	High-rise and other structures	• Poor communications
	Tunnels and underground structures	• Poor communications
Unsuitable Equipment	Hazardous conditions	• Water exposure • Visibility
	Personal protective equipment	• Self-Contained Breathing Apparatus
System Design	Inadequate infrastructure	• Lack of repeaters and tower sites • Lack of channels and frequencies
System Capacity	System capacity	• Inadequate capacity
Interoperability	Mutual aid	• Cannot communicate
	Other city departments	• Cannot communicate

POOR RECEPTION

International Border

- **Problems –** Departments located on or near the Canadian and Mexican borders of the United States often experience problems with signal strength and interference. Along the Canadian border, some localities have limited frequency space because Canada is reclaiming some of the VHF frequencies and essentially narrowing the available bandwidth. Localities located on the Mexican border are often plagued with interference from sources across the border.

- **Solutions** –The cities of Bellingham and Everett, WA, which experience radio communications difficulties because of their proximity to the Canadian border, are upgrading to an 800-MHz radio system. San Diego, CA, which experienced interference because of its location on the Mexican border, upgraded to an 800-MHz radio system in the early 1990s.

Topography and Terrain

- **Problems** – Hills, canyons, mountains, and forests can often cause interference and dead spots, and the shadowing from mountains also poses similar signal disturbances.

- **Solutions –** The City of Los Angeles encompasses 470 square miles that include hills, canyons, and mountains. Its fire department often experiences coverage issues because of this diverse topography. To overcome these challenges, Los Angeles has worked carefully on the strategic design and placement of radio system infrastructure (such as towers and repeaters). The Boulder Rural Fire Department even uses "human repeaters" when necessary. The City of Portland, OR, located behind the West Hills and close to volcanoes Mount Hood and Mount Saint Helens, experiences similar dead spots and communications difficulties. To combat these obstacles, Portland constructed a large antenna above the West Hills.

Neighboring Jurisdictions

- **Problems –** The radio systems of neighboring jurisdictions sometimes cause interference for fire departments. This occurs when adjacent towns operate on similar frequencies, and can sometimes prevent one department from sending or receiving messages. One jurisdiction may be at a higher elevation than the other and have higher towers.

- **Solutions –** The Springfield, NJ Fire Department has taken steps to solve their interference problems with local jurisdictions and discussions are underway to investigate the feasibility of trunking the current radio system. This may prove an effective alternative to upgrading; in Springfield, there are not enough frequencies available for the department to transition to an 800- or 900-MHz system. Gettysburg, a rural city in Ohio, would like to upgrade it current radio system too, but does not have the funds to do so.

Wireless Communications

- **Problems –** Many jurisdictions experience problems with the Nextel cellular phone system. The Nextel system, which operates on the 800-MHz band, seems to be incompatible with the pre-existing radio communication systems also in the 800-MHz band.

- **Solutions –** Fairfax County, VA's public safety system is experiencing system coverage degradation from Nextel (interference), and has proposed moving Nextel out of the 800-MHz band. The county has developed this plan as a means of avoiding reorganization or restructuring of its public safety radio system.

  Portland, OR, which experiences similar problems, had Nextel and the fire department swap frequencies to solve the problem. The fire department gave up a channel on the end of their radio spectrum for Nextel's channel in the middle of the city's band.

  Clark County, NV is awaiting final approval between the FCC and Nextel on a plan that addresses interference to public safety communications in the 800-MHz band. This plan is known as the Joint Commentor's Consensus Plan.

INTERIOR COMMUNICATIONS – LARGE STRUCTURES

High-Rise and Other Structures

- **Problems –** One of the most significant problems facing firefighters inside a high-rise structure is the ability to communicate reliably among firefighters and with the command post. Portable radios often do not have the RF power output necessary to communicate through the barriers inside the structure and reach the outside. Many of the cities reviewed have problems communicating during high-rise operations.

- **Solutions –** Jurisdictions have managed this problem in different ways, depending on the specific nature of the communication challenge. Pittsburgh, which uses a centralized UHF communications system for all city services, encounters most of its problems in large and high-rise structures, especially sub-ground or tunnel areas. The city solves communications problems with a talk-around system that uses two-way radios for a ½-mile communications radius.

  Dallas, TX and San Diego, CA solve their high-rise and structural communication problems by relaying messages via "runners" through egress stairwells. For special events, such as the 2003 Super Bowl and events at the San Diego Convention Center, the San Diego Fire Department uses a Mobile COW (Cellular on Wheels), which acts as a mobile antenna to repeat communications outside a building.

In Charlotte, NC the fire department is testing a mobile repeater and has reported some success in overcoming communications difficulties during interior operations, where the department uses simplex mode—radio to radio—to communicate. A mobile repeater adds signal strength to the interior of the structure, allowing firefighters to better communicate.

Schaumburg, IL has a new 800-MHz system with four antenna sites. Fire department officials have reported dramatically improved communications during structural firefighting events. Before the new system, the fire department experienced dead spots throughout the village and problems in high-rise structures, typically constructed of concrete and Lexan glass. Additionally, new building codes required installation of signal boosters during construction for certain types of buildings.

Phoenix, AZ uses a conventional direct radio communication system in VHF. Two tower sites and diversity receivers comprise the primary infrastructure. The receivers allow the department to communicate without talk-around channels or runners. The diversity receiver operates like small radio towers and accepts the emitted radio signal on several antennas with a radius of 2 square miles. The department operates 24 VHF channels, and there are 36 diversity receivers per channel. This system works well in high-rise and other large structures. However, it does have its drawbacks. The two most common challenges are fade and feedback.

Many new buildings in Boston, MA, Clark County, NV, and Fairfax County, VA are installing bi-directional amplifiers. Bi-directional amplifiers, commonly known as BDAs, are used for improving/correcting portable radio communications to, from, and within large structures. These BDAs let fire departments operate their fire department channels within a building.

Tunnels and Underground Structures

- **Problems –** Road tunnels, often constructed with massive amounts of concrete and steel, create a manmade barrier to radio communications and pose a serious threat to firefighters. Other underground structures yield similar problems.

- **Solutions –** The City of Boston is attempting to preempt communications difficulties while it constructs a major underground expressway. The city reported success with using a "leaky cable" device in its Ted Williams Tunnel, and plans to install the same device in the new expressway. This leaky cable is a "byproduct of conventional coaxial cable with small slits cut through its layers that allow RF signal to seep out in amounts strong enough to cover small areas of square footage." [**296**]

UNSUITABLE EQUIPMENT

Water Exposure

- **Problems –** Prolonged exposure to water can decrease the effectiveness of portable radios. If a radio system is antiquated, water exposure can cause serious equipment damage and endanger firefighters.

- **Solutions –** The straightforward solution to water exposure problems is to purchase new, waterproof equipment. The Milwaukee, WI Fire Department has reported no problems with its new portable radios; they are specially designed to be submerged in water without damage.

Self-Contained Breathing Apparatus

- **Problems –** Many firefighters struggle with the portable radio and the ease of using it in a zero-visibility environment while wearing bulky fire department gloves.

- **Solutions –** The Schaumburg, IL Fire Department alleviates this problem by programming the extremes of the channel selector on the portable radio (selector turned all the way left or right) to the same, recognizable channel (usually dispatch) regardless of zone selection. So, if the firefighters operating in a zero-visibility environment accidentally change the radio from the tactical operations channel and cannot find it again, they can turn the selector all the way in either direction and still talk to a dispatcher in the event they need help.

SYSTEM DESIGN

Lack of Repeaters and Tower Sites

- **Problems –** Some of the fire departments reviewed experienced problems with radio communications due to a lack of essential infrastructure, such as repeaters and towers. In most cases, system infrastructures were insufficient. In other cases, poor system design and placement of infrastructure were the problem.

- **Solutions –** San Francisco alleviated problems by switching from a 400-MHz radio system to an 800-MHz radio system 8 years ago. The newer system accommodates more working channels (16, with three controlled for dispatch and one for each of the 10 battalions) and interoperability. The department has also added more towers and repeaters and is currently upgrading the system with portable repeaters, as well as moving repeaters to higher elevations to prevent interference from high-rise buildings.

Similarly, the Wichita, KS Fire Department solved communication difficulties by switching to an 800-MHz trunked system 10 years ago. Each company officer has a portable radio.

Chicago has solved communication problems by deploying a diverse multi-simulcast radio system and 10 transmitter sites (per channel). The system has up to 32 receivers within any area it serves (12 square miles). Because of this, communications with dispatch via portable radios have highly improved.

Los Angeles's problems from the city' size and diverse terrain and topography have been alleviated by incorporating backup repeater sites in these areas. The city has solved communication problems in subways and tunnels by wiring them with underground cables, which carry a signal for four or five of the fire department channels.

Lack of Frequencies or Channels

- **Problems** – Some fire departments have a limited number of tactical channels on their radio systems. These departments are vulnerable to communications problems when multiple incidents occur at the same time.

- **Solutions –** Everett, WA accesses a single dispatch channel and a single tactical channel, which can complicate communications during fire incidents. To alleviate concerns, the department is upgrading to an 800-MHz system.

SYSTEM CAPACITY

Many cities reported no concerns with system capacity, including Austin and San Antonio, Phoenix, Charlotte, Los Angeles, and Portland. These departments have standard operating procedures designed to shut down various parts of the system (e.g., the private line function and interconnect system of an 800-MHz radio system) to ensure no overcapacity.

INTEROPERABILITY

- **Problems –** Often departments do not have the capabilities to communicate with other emergency departments (e.g., fire, police, public works) or with another neighboring jurisdiction using their own communications system. This is essential for exchanging information in mutual-aid calls, mass casualty incidents, or special events.

- **Solutions –** Many departments are currently in the process of upgrading its communication systems to 800-MHz, specifically for interoperability purposes. Others have used alternate technologies or methods to improve or create interoperability. Following are a few examples.

A Boston Fire Department chief, acting as the incident commander, is collocated with an incident commander from another department.

In Charlotte, NC all mutual-aid partners and chief-level officers in other departments are provided with radios. Similarly, departments in Dallas and San Antonio communicate with the police department through a "patch" system. Dispatch will patch police and fire together, and they can talk directly to one another.

Chicago is developing a permanent solution to its interoperability problems, which include an inability to talk directly with law enforcement and EMS, as those departments operate on a different radio system. Because the fire department and EMS respond together on most incidents, the fire department has access to the EMS radio system (VHF) and the police and EMS radio system (UHF). Additionally, the department deploys a command vehicle, outfitted with a suite of radios that allow communication with all departments, to every major incident.

In San Diego, the fire department uses a Motorola 800-MHz system, which has been in place for 11 years. The operations units also carry VHF portables because neighboring departments (recipients of mutual aid) use this system (e.g., California Department of Forestry).

Communications Problems in Firefighter Fatalities

Fire department communications have been cited as a contributing factor to the death or serious injury of numerous firefighters. The deaths have not been directly attributed to failures in radio communications. Rather when communications issues are cited, they are frequently problems in transmissions, standard operating procedures, or unsuitable equipment. Even when such issues strand a firefighter, casualties are generally associated with the fire, and few records are kept on the issues with portable radios. But review of the various departments and of fire literature revealed some instances where failed radio communications were at issue.

In Syracuse, NY, four firefighters perished in 1978 while fighting a fire in a three-story, wood-frame apartment building. Reports attributed the deaths to failed radio communications. While failed radio transmissions contributed to past casualties, Syracuse was of particular note due to the number of staff who died.

The trapped firefighters, confined on the third floor by a rapidly spreading fire, made several calls for help which went unheeded by dispatch, but which were heard by an observer who immediately reported the transmission to a fire officer on the scene. Thirty-seven minutes into the incident, the first of the fatalities was found. [**123**]

Five firefighters were killed at a fire in Hackensack, NJ when the bowstring roof of a car dealership collapsed. Due to changing fire conditions, a battalion chief ordered all personnel to evacuate the structure. This order was never acknowledged nor repeated by the dispatch center. The roof fell before the personnel could exit the structure**. [335]** Hackensack had only one radio channel for both dispatch and tactical operations. Heavy traffic overwhelmed the inadequate tactical channel, and the firefighters' transmissions for help were overridden by transmissions from dispatchers.

A similar situation occurred in Brackenridge, PA after the floor of a commercial structure collapsed. Heavy radio traffic led the crew to switch from the primary incident channel to an alternate tactical channel — effectively cutting them off from the incident commander and the rest of the crews on the scene. The Brackenridge casualties resulted from radio operational issues; with only one channel for dispatch and tactical operations, the system was overloaded and dispatchers overrode transmissions from the fire ground**. [339]**

Unsuitable equipment and product design resulted in the deaths of two firefighters and the injury of a third at the Indianapolis Athletic Club during 1992. The injured firefighter, a captain, reportedly activated the emergency button on his portable radio and made several unsuccessful attempts to radio for help. While the push-to-talk button on the radio was easy to engage with a gloved hand, he had to remove his glove to use the emergency button, and seriously burned his hand**. [337]** Insufficient training might have played a role in the casualties. The department had switched to an 800-MHz system two weeks before the fire. This switch could have been responsible for the delay in acknowledging and processing a request for a second alarm.

Two firefighters were killed and two more injured while fighting a townhouse fire in Washington, DC in 1999. The firefighters were caught in a flashover while attempting to suppress a basement fire. Department personnel were using frequencies that were 15 kHz apart, as recommended by NFPA. But in the past they had experienced problems with interference or bleed over between channels. This interference may have affected the ability of personnel operating on the scene to hear messages from the incident commander. **[338]**

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.

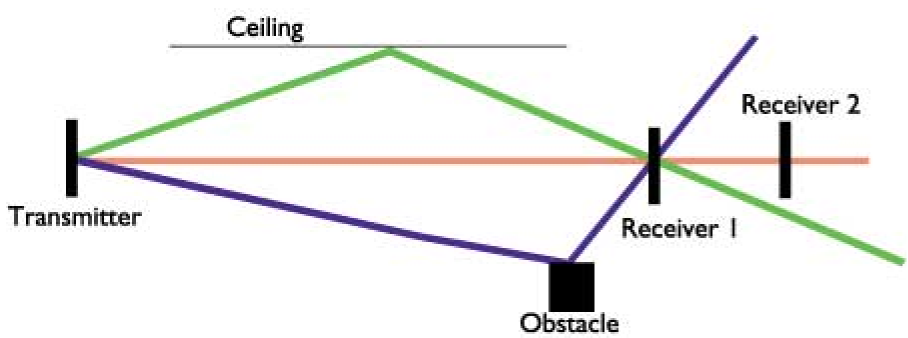
The individual signals caused by reflection, diffraction, and scattering that arrive at the firefighters radio are collectively known as multipath signals. Multipath is a set of

[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.

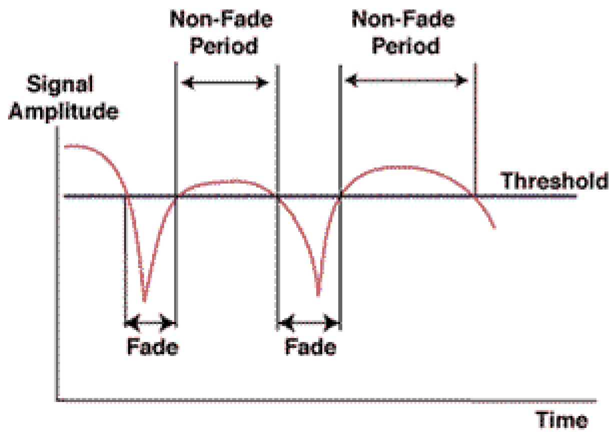
Multipath signals (that is, reflection, scattering, and diffraction) also cause radio signal distortion (noise) as well as additional signal propagation losses (attenuation). Figure 2 shows two key properties of multipath fading, amplitude and period. The fading amplitude is the amount of signal amplification 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.

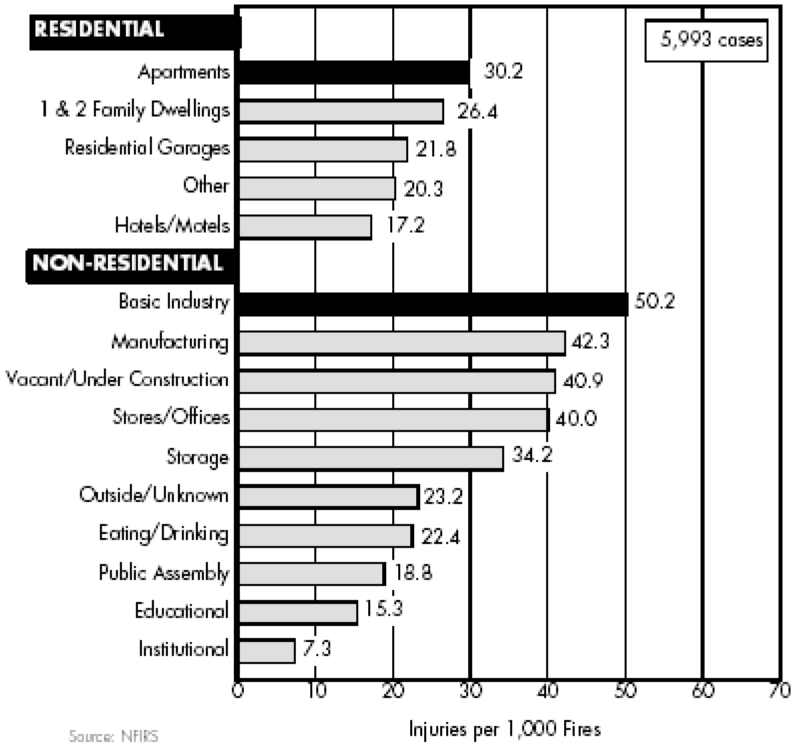
In general, the radio systems used by firefighters do not have the required features for operation in difficult indoor areas.

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

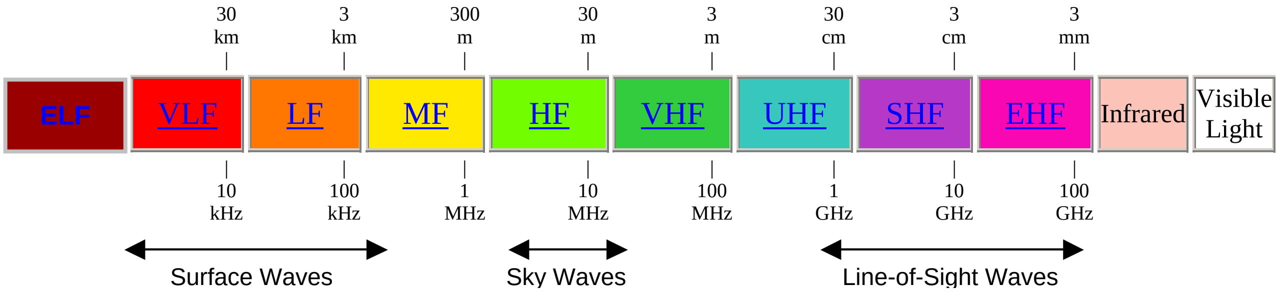
Radio Spectrum Considerations

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.

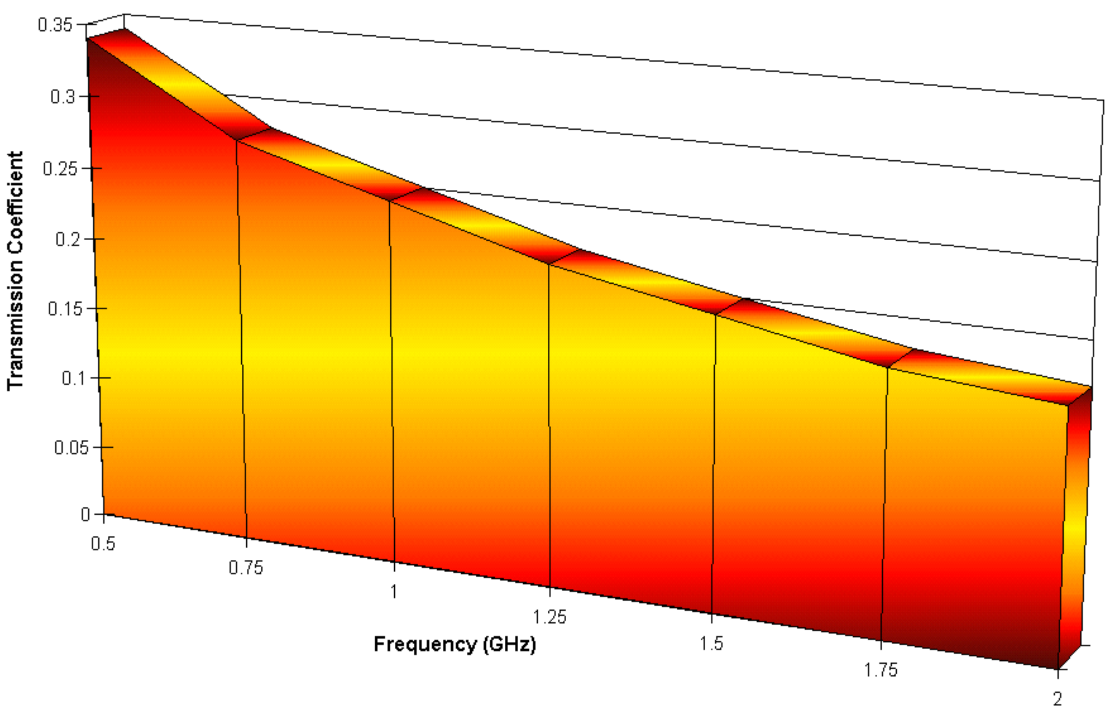
Super High Frequency (SHF) – Radio location, radio navigation, point-to-point microwave, and satellites are users of this band. This band has unlicensed frequencies.

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



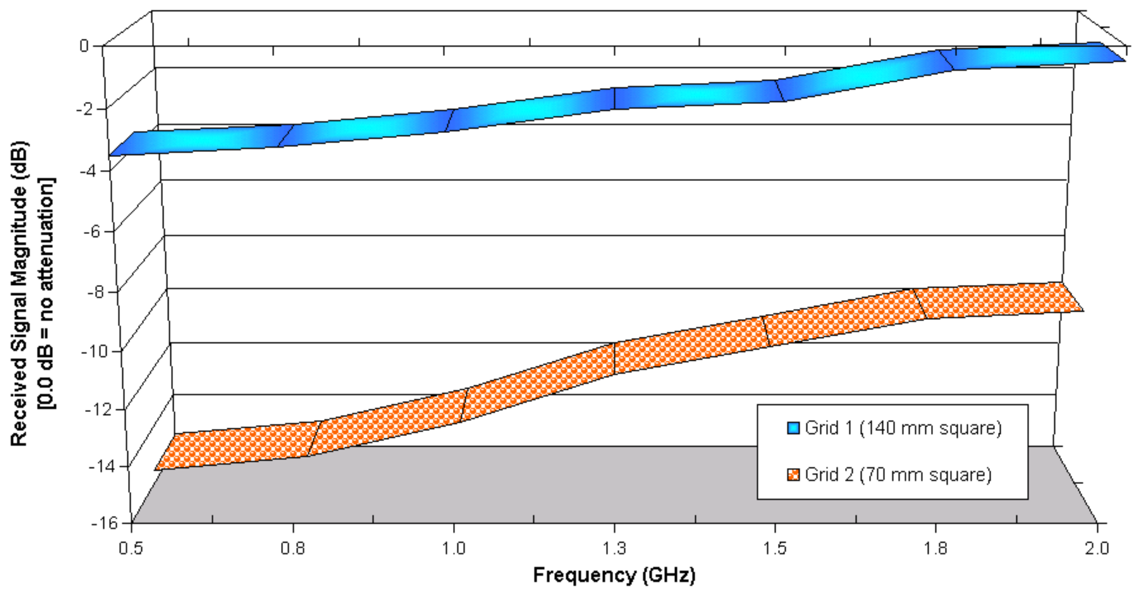
Source: Adapted from NIST Construction Automation Program Report No. 3: *Electromagnetic Signal Attenuation* in Construction Materials, National Institute of Standards and Technology, Gaithersburg, MD. October 1997.

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.

CHAPTER V: CURRENT TECHNOLOGY STATUS, KNOWLEDGE GAPS, AND RESEARCH NEEDS

The literature search for technologies to solve firefighter communications and personnel location problems caused by poor RF signal propagation in structures identified several promising technologies, including ultra wideband (UWB), mobile area networks (MANet), other spread spectrum, and use of frequency bands that couple inductively/ parasitically to conductors, power line distribution, among others**.** This chapter discusses each of the promising technology areas identified during the literature search. Included in each technology section is a discussion of what the technology is, how it is applicable to firefighter communications or location problems, current status relative to firefighter communications including research to date, and, if applicable, products that demonstrate current or potential usefulness to the firefighter communication problem and knowledge gaps. Finally, for each technology, a series of recommendations are included which, if implemented, could lead to improved radio communications for firefighters on the fireground.

Many of the areas of promise discussed in this section are state-of-the art and their descriptions very technical. While every attempt has been made to describe the technologies in a straightforward manner, to fully address the nuances of the concepts and to correctly describe the technology, the level of information and detail may exceed the interest of the casual reader.

Ultra Wideband

Ultra wideband (UWB) is not a truly new technology. Marconi employed the concept with his spark gap transmitter over 100 years ago. First fully developed in the 1960s for the U.S. military, the bulk of work was in the classified area for about three decades. The technology has been in use in radar systems for some time because the wide bandwidth results in very accurate timing and allows accurate ranging. [**208,286**] Recent advances in switching technology are driving the cost of UWB implementation lower, and many believe UWB is the potential next wave in commercial wireless communications. UWB offers the promise of:

- Precision range/radio location systems
- Robust communications in severe multipath environments such as buildings
- Low-power systems with long battery life
- Promises to provide a means to share spectrum without affecting current radio signals due to its very wide band, very low power emissions that appear as noise to other non-UWB receivers. [**301**]

UWB technology has many applications including communications, precision geolocation, and radar. Its recent application to high-rate digital communications, particularly for use in urban environments where robust propagation in structures is required, is an innovative technique that combines the ability to transmit high-rate digital data at low power. Impulse radio is a form of UWB spread spectrum signaling with multipath mitigation properties that make it particularly applicable for application in severe multipath environments (such as those found in urban settings and within structures). [**152,210,282,287,305**] UWB, requiring a fading margin of only 1.5 dB[9], has demonstrated the ability to transmit within structures where higher power narrow band signaling fails. [**305**] Many researchers and commercial companies have come to the conclusion that UWB technology is the most promising solution for communications and precision location of firefighters in urban areas and particularly in buildings where conventional Global Positioning System (GPS) or almost any communications using a sinusoidal-based waveform is subject to the issues of multipath fading. It remains to be seen whether UWB will emerge as a supplement or a replacement to cellular radio and other more traditional RF technologies.

TECHNOLOGY DESCRIPTION

UWB is a general term for a class of signals that have much wider bandwidths than those found in traditional narrowband or wideband communication systems such as trunked radio (narrowband) and recently launched third-generation (3G) cellular (wideband). UWB is differentiated from these signal classes in two ways: communications bandwidth and the use of a carrier-less RF implementation. For communications bandwidth, the FCC is considering two definitions: (1) bandwidth greater than 25 percent of the center frequency at the –10-dB points or (2) RF bandwidth greater than 1 GHz. [**292**] This is in contrast to wideband 3G cellular, which occupies less than 4 MHz of spectrum, or narrowband trunked radio, which occupies 25 kHz. A UWB transceiver can function in a carrier-less fashion because it directly modulates an impulse with extremely sharp rise and fall times thereby generating a signal with a bandwidth on the order of several GHz. [**142**] Narrowband and wideband systems use an RF carrier to translate a baseband signal to the desired RF operations band. The transceiver is very simple for a UWB system because of the low power transmitted and the carrier-less implementation. Typically, the system will not need a power amplifier and will consist only of a pulse generator fed directly into an antenna. To demodulate the signal, a UWB receiver coherently detects the signal using a correlation receiver. No complex analog carrier circuitry is needed; hardware costs can be kept low once the UWB-based products become mature and produced in quantities. Currently, the prototype-based systems are still relatively larger and more expensive as the technology is still new.

In a UWB system, a transmitter emits sequences of impulses that are detected by a corresponding receiver whose front-end amplifiers are synchronized and time-gated to the transmitted pulse sequences. Data information to be sent is modulated onto certain parameters of the transmitted impulse. Such parameters may include the pulse position, amplitude, or orientation. For example, using pulse position modulation, the transmitting system may time advance a pulse to indicate '1' and time retard a pulse for a '0'. [**281**] A single bit of information is typically spread over many pulses, and the receiver system coherently sums up the correct number of pulses to determine the bit value. Depending on the system vendor and application, some UWB systems transmit many closely spaced

[9] This fading margin is very low; a typical indoor cellular system is designed with 20 dB of fading margin.

short pulses, and others may transmit fewer pulses with larger interpulse spacing and some use amplitude modulation. [**106**] Coherent summing provides integration gain in the receiver. To allow a multiple access environment, each user would be assigned a unique pseudo noise (PN) code similar to conventional CDMA systems (such as the cellular service provided by Sprint or Verizon). This PN code would be used to generate a unique sequence of time shifts on a pulse train that allows pulses to be discriminated from one user to another. As each transmit-and-receive pair is active only for a very short period of time, many transmit-receive pairs, each with its own unique pulse sequences in time, can operate within the same area without causing mutual interference.

One important advantage of spread spectrum communication techniques is the ability to mitigate multipath problems. Impulse radio technology has the ability to nearly eliminate the adverse effects of multipath fading. Typically, multipath signals result from reflections of the original signal. These multipath signals will, in general, travel different length paths to the receiver with the result being each will have a different phase. They add together and, depending on the phase, can increase or decrease the received signal magnitude. In UWB systems with very short pulses, the delayed, reflected pulses could be detected and ignored. Studies that tested fading performance in homes and office buildings found minimal multipath effects [**282,287,293**] Other researchers are working on a Rake receiver UWB implementation which will allow the combining of various multipath signals to improve receiver performance similar to cellular CDMA systems. [**306**]

UWB also has important advantages in transmitting through building materials and structures. Generally, building materials show increasing attenuation of RF signals as frequency increases. For penetrating a building with an RF signal, a low frequency is generally better than a high frequency. UWB is carrier-less and, therefore, covers the spectrum from near dc (0 Hz) to the upper end of the signal bandwidth, which can be a few GHz. A UWB system essentially "adapts" to the attenuation characteristics of the material it is passing through. For a given bandwidth, the center frequency of the UWB signal is low which makes for better propagation through and lower absorption from materials. Nevertheless, in spite of these advantages UWB transmissions are still inherently RF signals and are fundamentally subject to the same absorption characteristics as other sinusoidal-based radio transmissions. In this regard, the center frequency and other parameters of a UWB-based system must be carefully selected to achieve optimum performance for a given application.

APPLICATIONS

Communications and Networking

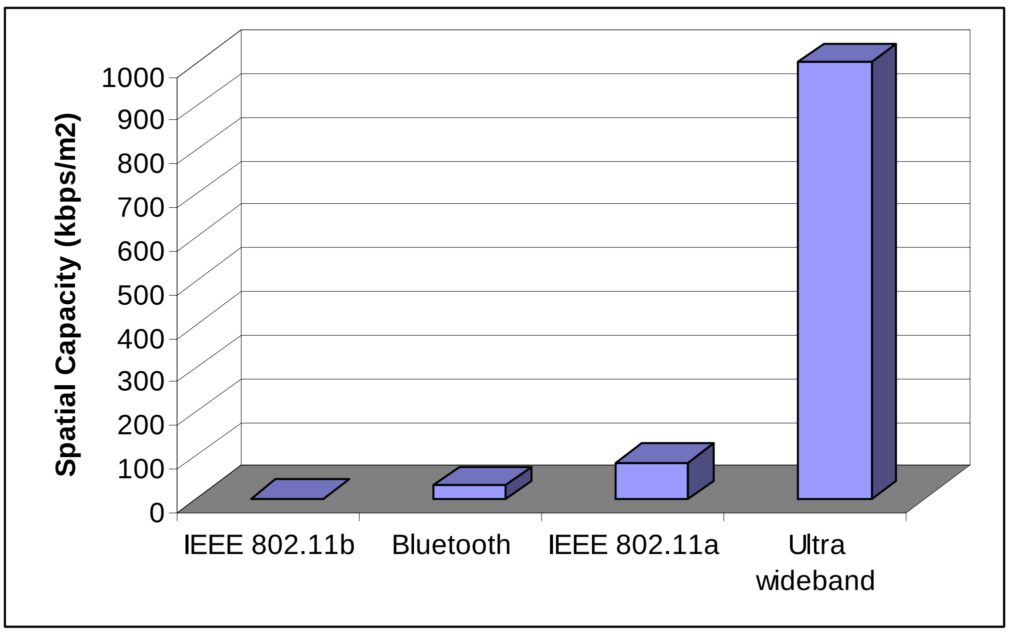
Several technologies are competing for the high-data-rate, short-range market for which UWB is suited. These technologies include wireless LAN (IEEE 802.11a, IEEE 802.11b) and Bluetooth (Table 8). Figure 7 shows that none of these competing technologies provide nearly as much spatial capacity as UWB. [**142**] UWB has been demonstrated to rates over 100 Mbps with the potential to go to 500 Mbps. [**306**]

TABLE 8: COMPARISON OF UWB TO OTHER WIRELESS SYSTEMS

Technology	Data Rate	Range	Cost	Power	Spectrum	Comments
UWB	50–100 Mbps (theoretically up to 500 Mbps)	500 ft	Low	Low	UWB	Only high-data-rate WLAN in 300–500-ft range
802.11	54 Mbps	90–100 ft	High	High	5.0 GHz	Power, cost issues
HyperLan	25 Mbps	100 ft	High	High	2.4 GHz	European standard, same as 802.11b issues
802.11b	11 Mbps	250–300 ft	Med	Med	2.4 GHz	Speed issues
Home RF	11 Mbps	150 ft	Med	Med	2.4 GHz	Lost Intel support, speed issues
Bluetooth	1Mbps	30 ft	Low	Low	2.4 GHz	Speed issues

Source: [**50**]

FIGURE 7: SPATIAL CAPACITY OF UWB



Source [**142**]

The short pulses of UWB signaling are less susceptible to multipath fading and better able to penetrate building materials than competing technologies. These characteristics make UWB applicable to robust in-building communications. [**145,284**] Low-power transmissions will also extend battery life. Radio and radar systems could be developed that dynamically trade data rate, range, and power consumption/battery life. UWB is inherently secure as its low power, high bandwidth makes is appear to be noise to a non-coherent detection system. This makes it more difficult to intercept.

Imaging Systems

Motion detection and radar are natural applications for this UWB technology. Similar to other radar systems, UWB radar measures the roundtrip time and angle of arrival of reflected pulses. Because of the multi-GHz bandwidth of the system, the resolution can be as accurate as 3 cm. [**152**] This type of application requires a directional antenna system to determine angle of arrival. This requirement is a problem as development of directional antennas with this bandwidth is difficult.

Hand-held imaging devices with the ability to detect, range and sense motion of people or objects have been developed and commercially deployed for use by police departments. [**206**] An example of such a handheld radar device is Time Domain's RadarVision™. The technology has also been used to develop ground penetrating radar systems for applications such as mine detection.

Indoor Geolocation and Tracking

Using four reference receivers provides three-dimension location of UWB transmitters to centimeter precision because of the short, well-defined timing of the UWB pulses. Short pulses allow the direct path pulse to be differentiated from multipath reflections that lag in time. The UWB transmitter could be a communications radio providing voice communications combined with location or a UWB tag used only for location. [**152,284,327**] Each firefighter equipped with a UWB radio or a tag automatically and continuously transmits unique data to a set of antennas located at strategic points around the building whose positions are precisely known. In this manner, the precise three-dimensional location can be determined. These systems typically use either angle of arrival (AOA) or time difference of arrival (TDOA) techniques to determine the location. Conversely, the UWB transmissions can be picked up locally within the same room with a small antenna array mounted on the firefighter's helmet. This would allow the firefighter to not only determine his approximate location and detect or "see" others with radios or tags in a smoke-filled room, but also the identity of the other firefighters in the vicinity. Furthermore, using this system, the firefighter may also be able to detect the location of other UWB-equipped firefighters in adjacent rooms or floors. Receivers outside could detect the location of the firefighters as well. As of September 2003, this technology has yet to be demonstrated in practice despite several firms' work in this area.

RESEARCH AND PRODUCT STATUS

Research and product development using UWB technology is an area of significant activity. Two players in the UWB arena are Time Domain Corporation and Multi Spectral Solutions, Inc. (MSSI). Time Domain has focused on large-scale commercialization of UWB and has taken an aggressive approach to their intellectual property development with a suite of pioneer patents in this area. MSSI has remained smaller and more focused on specialized applications for both government and commercial users including geolocation. [**279,285**] In addition, a myriad of smaller companies and universities have made advances in both technology and prototype development of UWB-based systems, either independently or by teaming with one of the larger players. To date, commercial companies have shipped products using UWB technology to "see" through walls for use by police and firefighters as noted above. Æther Wire & Location, Inc., has demonstrated prototype devices for precise 3D location, and Intel has working prototypes of USB devices operating at 100 Mbps with predictions of 500 Mbps soon. These products operate in the unlicensed spectrum at 2.4 GHz and 5 GHz. Worcester Polytechnic Institute (WPI) is also pursuing a location and communications system that uses a UWB technology based on a form of orthogonal frequency division multiplexing (OFDM). [**188,235,298**] The advantage of using OFDM is that it is spectrally shaped to reduce interference to other RF communications. WPI expects to have a proof-of-concept demonstration running late 2004.[10]

Significant resources are being devoted to UWB research at universities, government agencies, and commercial companies. The most important research topics are:

- Developing reliable channel models to predict performance and to allow optimized transmitter and receiver design.
- Ongoing research in receiver design to take advantage of multipath reflections similar to the Rake receiver technology found in CDMA cellular systems to achieve signal processing gain.
- Developing highly integrated silicon solutions to drive the cost of UWB systems down. Time Domain has a three-chip solution at this time.
- Determining the effect UWB systems have on other communications systems such as cellular and GPS.

ISSUES

Regulatory

The FCC and NTIA jointly manage the radio spectrum in the United States. UWB devices cannot avoid emitting energy into both government and non-government spectrum; thus, FCC must coordinate rules with NTIA. UWB meets FCC Part 15 constraints on incidental radiation but needs a waiver due to the intentional nature of the radiation. [**143**] Recently the FCC gave UWB companies clearance to market their devices commercially, but only in a limited range of frequencies and with limited power. [**223**] The ruling restricted operation of UWB communications systems to low-power hand-held devices in the 3.1- to 10.6-GHz frequency band. While this specification could provide for some communications applications, the limitations are not practical for geolocation or radar. However, this was a step forward for UWB proponents and was achieved despite objections from the Pentagon as well as GPS and cellular operators.

Major regulatory issues remain. Usage and interference characteristics of UWB systems have become a heated argument in the telecommunications, broadcast, and navigation

[10] From a telephone conversation with Dr. John Orr, September 2, 2003.

communities. Numeric limits on UWB emissions and what techniques should be used to measure them are still being argued from both sides.

Although the UWB power levels are essentially white noise for most applications, there are still concerns of cumulative interference from widespread use of UWB devices in the same spectrum as conventional radio communication devices, including emergency services, GPS, and cellular networks. [**301**] The regulatory agencies are looking particularly at bands that are used specifically for fire, police, rescue, and other critical services. In February 2002, the "Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems (ET Docket 98-153)" was adopted. This memorandum mentioned the public safety sector as candidates for some UWB applications, but it did not include provisions for the several uses of UWB for fire and rescue. Industry proponents objected and provided several petitions for reconsideration, one of which was through-wall imaging systems specifically for police, fire, and rescue. In February 2003, the FCC published a revision to the 2002 docket. The memorandum includes several pages of discussion on the topic of firefighter and police safety. The proposed modification to the standards was adopted and somewhat relaxed the specifications for these applications. While this specifications relaxation was not a major technical concession, the acknowledgement of the importance and the shift in the FCC and NTIA to allow exceptions for UWB products for the public safety sector were steps forward for the UWB community. An excerpt from the FCC February 2003 memorandum opening the specification follows:

> *We agree that any technology that increases the survivability of our police, emergency rescue personnel and firefighters should be encouraged. As a result of the factors discussed in the preceding paragraphs, we are amending our rules to permit the operation of a through-wall imaging system with a center frequency above 1990 MHz at the Part 15 general emission limits. However, we acknowledge the concerns expressed by the commenters and believe that some additional operational standards should be implemented to ensure that operation of this equipment does not result in harmful interference to other radio systems that may also be employed for public safety purposes. We do not believe that any of these standards will cause operational difficulties.* [**163**]

The FCC has stated its intention to continue evaluating the potential impact of UWB devices on other communications services to see if changes are needed to the UWB standards. [**259**] Traditionally, the FCC, NTIA, and wireless community have allocated a specific and separate spectrum for each use to avoid interference. This concept has been followed since the inception of wireless communications. As a result, the notion that UWB will occupy the same spectrum as many of the critical functions is a change in thinking for all parties involved. These issues are being addressed by the FCC, NTIA [**201**], and many commercial UWB proponents, but a significant amount of work and testing needs to be performed before UWB becomes mainstream. This process could take several years. For systems operating within the current limitations, the power restrictions limit either the data rates or the effective range of these devices to a degree that could potentially cripple this technology. [**13**]

Other

UWB antenna development is lagging behind the remaining UWB system developments.

UWB receivers have not reached the level of development to incorporate techniques such as Rake receiver design needed to provide truly robust communications in severe multipath environments. [**280**]

There are some concerns about UWB's susceptibility to jamming by narrowband signals within the UWB passband. [**106**]

RECOMMENDATIONS

The public safety community should develop a position in regards to supporting UWB deployment and the minimum requirements needed for each firefighter application. If the fire community's position is to support this technology, then minimum requirements should be developed for firefighter applications. An organization, such as PSWAC, NFPA, or Project MESA[11] *should be used to make the community's position known to the spectrum-regulating organizations.*

The public safety community, using an organization such as PSWAC, NFPA, or Project MESA, should support antenna research and provide input on firefighter-specific antenna requirements.

The public safety community, using an organization such as PSWAC, NFPA, or Project MESA, should support research and design of advanced receiver architectures such as the Rake receiver.

Research into electromagnetic susceptibility and compatibility should be supported through organizations such as PSWAC, NFPA, or Project MESA. Ideally, power and frequency restrictions will be lessened to make UWB more widely applicable for public safety applications.

Mobile Area Networks

Advances in mobile ad hoc wireless network (MANet) communications techniques may make it possible for users to communicate more reliably than with a conventional radio system. Often, a user may be located inside a building where communication is possible with other neighboring radios also inside a building, but not with the tower or with radios located outside the building or in other areas of the building where the RF attenuation is too significant. This connectivity scenario brings rise to a new concept where each peer

[11] Project MESA is an international partnership producing globally applicable technical specifications for digital mobile broadband technology, aimed initially at the sectors of public safety and disaster response.

radio is capable of acting as a relay or router and provides a multiple hop communication relay chain. In this case, one user, deep inside a building, may be able to communicate with another radio closer to the building perimeter. The perimeter radio then acts as a relay between the first user and the tower to provide successful communications. Originally developed for military and commercial cellular applications, this concept is applicable for firefighters and other first responders. Commercially, this technology has been gaining increased popularity for wireless voice and data networks. For example, potentially large cost savings could be achieved for cellular operators if they could limit the number of base stations a tower would have. The concept has become so significant that it has inspired the forming of a new section of the Internet Engineering Task Force (IETF) on Mobile Ad hoc Networking. A MANet is useful wherever connectivity is temporary and on-demand such as a conference or meeting room, military team, sensor telemetry, and disaster or first response teams.

TECHNOLOGY DESCRIPTION

An ad hoc network is a network that has no fixed infrastructure such as base stations. Nodes in the network that are mobile and connected by wireless links are called a mobile ad hoc network. [**206**] They are designed to be quickly and autonomously deployed without prior planning or preinstalled infrastructure. Whenever two or more nodes are within range of each other, a MANet will spontaneously form providing network functionality including voice-over IP, a technique for voice communications over a network. These nodes or routers are free to move randomly and organize themselves arbitrarily. As a result, the network's topology may change rapidly and unpredictably. [**132**] Multihop communications are used to communicate between nodes in the network. Multi-hop means that data from the originating node travels to the “best” nearby node, which then passes the data to its best nearby node until this series of hops gets the communication to the destination node. Each node acts as a router in cooperation with all the other nodes in the network. Because this networking approach is designed to form and maintain a network without user intervention or infrastructure, it would operate just like a traditional VHF or UHF radio from a firefighter’s point of view. He will not need to know or notice that when he speaks into his radio whether the communication reaches its destination via multiple hops or relays.

The important features of a MANet are [**302**]:

- Network topologies are dynamic. These nodes or routers are free to move randomly and organize themselves arbitrarily. Nodes can join or leave a network at any time. As a result, the network's topology may change rapidly and unpredictably.
- The network must be able to function on battery power. The restriction of available battery power means that the network requirements and capabilities must be designed with energy consumption in mind.
- Depending on the location of each node/radio the radio propagation conditions may be quite different. Thus the bandwidth of the wireless links is not consistent across the network. Links may drop and reconnect due to fading and other typical mobile communications effects.

- The physical security of ad hoc networks is lower than wired networks because of the use of wireless links and lack of infrastructure support.

These characteristics of MANet are what drive the research and product development activities for this technology. Important areas for understanding the potential, issues, and risks of MANet are routing, security, quality of service, wireless link technology, and standardization efforts.

The requirements imposed on MANet networks can be daunting as they include complex coordination and switching protocols, algorithms requiring high computational bandwidth, real-time handoff with other network nodes, sophisticated modulation technologies, and relatively high-date-rates (as compared with existing single-channel voice radios). Historically, communications architectures have tended toward pushing the network intelligence into a central hub. Since there are only a few hubs or one hub per system, it was cost-effective to have expensive RF components and computational elements. MANet-based systems push the networks "intelligence" into the handset. In spite of the added complexity, user demands still require small, durable packaged devices with long battery life. This remains a technical challenge.

Routing technology is perhaps the most significant technical challenge for MANet systems. [**136,137,156,157,270,272,273,274,275,276,277**] Routing software development is driven by the constraints of link bandwidth, node power consumption, and the dynamic nature of the network topology. The protocols under consideration are able to form and maintain the network with minimal communications. This conserves link bandwidth for other services (voice over IP, for example) and extends battery life by limiting the time the node is transmitting. Because of the dynamic nature of the network, typical Internet routing protocols are not applicable. Most of the MANet protocols use distance vector algorithms, which only send routing tables to near neighbors rather than to everyone on the network, as do Internet routing protocols.

Security becomes a difficult issue in a system such as this, since the nodes are mobile and can be connected dynamically in an arbitrary and random manner. A rogue mobile device could to wreak havoc in a network where each peer has autonomous capability and control. Eavesdropping is also a concern with wireless links.

Quality of service in a MANet has more constraints than a wired network. These additional considerations are constant topology changes, bandwidth limitations, and limited memory and processing capabilities of network nodes tasked with routing communications. The limited memory and processing that each node has is a particular problem because of the dynamic topology. The routing protocols and tables require nodes to carry out complex calculations and store significant amounts of data about the routes including bandwidth. [**271**]

There are several candidate wireless link technologies under consideration for mobile ad hoc LANs. These include IEEE 802.11 Wireless LAN, UWB, and HyperLAN/2.

Of these 802.11 is the most widely used and is suitable for relatively short distances. It provides up to 54 Mbps (802.11a or 802.11g) transmission rate and operates in the 2.4-GHz band. This standard was not developed with mobility in mind and has some serious drawbacks. Studies have shown that it has poor scalability, as the throughput per node drops very quickly as the network grows. [**307**] It also has problems with handovers if the mobility of network nodes is high. These may not be problems for typical firefighter deployments with handheld radios.

UWB is being used in some MANet projects. [**283**] It offers to provide high-date-rates at relatively low cost and link performance that is not adversely affected by multipath effects. A MANet using UWB signaling would combine the benefits of both technologies. The synergy between the excellent in-building propagation characteristics and the increased reliability offered by a peer-to-peer routing technology may offer a reliable in-building communications system.

HyperLAN/2 is a standard developed by ETSI intended for wireless LANs. Its properties make it suitable for MANet applications. It provides high-speed data, 54 Mbps, efficient handovers for supporting mobility, and power-saving support. It also provides reasonable security by including authentication and encryption. It is relatively costly.

Many of the technologies involved in wireless ad hoc networking are either established standards or have been submitted in draft form to standards bodies such as the IETF MANet Working Group. IEEE 802.11 and HyperLAN/2 are both established standards while most of the routing protocols are in draft status. Some areas are nowhere near having standards. Security and quality of service are areas with no near-term standards in progress. This lack of standards is an impediment to wide spread use of MANet.

APPLICATIONS

Communications and Networking

This technique provides a wireless network approach analogous to the standard RF bi-directional amplifier approach that normally uses leaky feeder or coax and antennas for interior RF distribution.

Although prototypes and demonstration projects exist using MANet approaches, no commercial systems suitable for firefighter use were found. Several commercial products exist that partially demonstrate MANet capabilities:

- *Vocera Communicator and Cisco IP Phone*: These devices provide voice-over IP. Neither of these devices uses an ad hoc approach; instead they are implemented with infrastructure mode IEEE 802.11b using fixed wireless access points whose location must be determined by using standard RF planning techniques. They do demonstrate voice over IP on a wireless network.

- *Nokia RoofTop Wireless Router*: This device acts as a wireless LAN access point for users within range and forms a fixed ad hoc network with other Nokia

RoofTop Wireless Routers to allow the network to function around obstructions such as buildings. It operates in the 2.4-GHz unlicensed band with a speed of 1–2 Mbps.

- *Radiant Networks Meshworks*: This product also forms a fixed wireless ad hoc network and acts as a wireless access router similar to Nokia's but with data rates up to 25 Mbps duplex.

- *Mesh Networks Mesh-Enabled Architecture (MEA)*: MEA provides mobile Internet and geolocation in an ad hoc network. Mesh Networks uses a proprietary QDMA modulation for the 2.4-GHz-band radio link. The network supports multihop communications and fixed wireless routers.

The U.S. Army and Marine Corp have deployed operational MANet systems. [**302**,**309**] The Army operates a system called Tactical Internet, which is a large MANet consisting of several thousand nodes. The nodes consist of man-portable and vehicle-mounted devices. The Marines have deployed a smaller MANet called in its Extending the Littoral Battlefield program. This network uses airborne relay nodes to which land and sea units connect using a Lucent WaveLan card that has been modified for longer range. Neither of these networks uses IETF MANet protocols and do not appear to support voice-level quality of service. Little detailed information is available on these implementations.

Indoor Geolocation and Tracking

One concept proposed to the National Institute of Standards and Technology (NIST) uses a MANet combined with the capability of UWB links to provide a fully integrated multifunction voice, data, and telematics system. This device would provide multiple critical functions including in-building location, local detection of colleagues, and multinodal communications. [**206**] The ultimate use of such a system could provide a unified fire safety network. The combination of a personnel location system with a GIS-based floorplan of the building and fire-spread modeling software could become an essential tool in fire suppression operations. While some of these concepts may appear to be far fetched, most of the core technology is available in pieces to make a fire safety network a reality.

Another approach proposed is to use "data bags" for MANet routing stations in addition to the carried handsets. These data bags are UWB transceivers that can act as relay points for the geolocation. In this architecture, the standard UWB transmitter tags carried by the firefighters would transmit at a power level in accordance with the existing FCC recommendations. This approach becomes feasible because the data bags act as mini-base stations inside the building, as opposed to other approaches that involve the use of antenna arrays located at points on the outside perimeter of the building. In this case the RF-shielding effect of the building can work to keep the radiation inside the structure and not to interfere with other communications and GPS used on the outside. In addition, the data bag also be used as a "sensor pack" to perform critical readings of temperature and other data useful in suppressing a fire. This approach has the disadvantage of the data bag becoming expendable.

RESEARCH AND PRODUCT STATUS

Mobile networking is an area of active research and product development by a number of organizations. NIST, for example, has three laboratories—Information Technology, Building and Fire Research, and Manufacturing Engineering—working together on a first responder testbed that uses an IEEE 802.11-based MANet to provide robust communications and radio location within an office building. [**189**] Recently, the testbed was used to demonstrate the ability of the MANet to accurately determine the location of each of the network communicators as well as voice communications. In September 2002, Information Systems Laboratory (ISL) received SBIR funding to investigate the feasibility of a system called the Wireless Firefighter Lifeline to locate, track, and monitor firefighters inside of buildings to within 1 meter. [**166**] In addition to tracking firefighters, the proposed system also provides biometric data such as heartbeat and respiration as well as external temperature and air bottle level to the fire commanders. ISL will show the feasibility of the concept through a combined modeling and measurement program. Several other companies are developing applications that fuse a MANet with UWB. Among them are Æther Wire & Location, Inc., which is developing a networked location system under contract to DARPA, and WPI, which is developing a combined location and communications system. [**300**] Florian Wireless is investigating the data bag concept described above.[12]

Routing protocols are being intensely researched. [**136,137,156,157,270,272,273,274, 275,276,277**] The routing algorithm faces unique challenges in a mobile environment. The most challenging aspects are the dynamic network topology, lack of centralization, potentially large networks both in numbers of radios and in area covered, the wireless links, and security considerations. Numerous algorithms have been proposed for application in ad hoc networks, each having a unique set of advantages and disadvantages. Requirements such as self-starting/self-organizing, scalability to large networks, computational complexity, routing reliability, link establishment, switchover time, blocking constraints, and queuing constraints are being assessed. Some top candidates are: [**136,137,156,157**]

- Ad Hoc On-demand Distance Vector
- Landmark Routing
- Temporally Ordered Routing Algorithm
- Dynamic Source Routing
- Fisheye State Routing Protocol
- Zone Routing Protocol
- Optimized Link State Routing

[12] This information is based on verbal and email correspondence between Rich Meyers of System Planning Corporation and Florian Wireless personnel.

Architectural approaches being investigated include full autonomous peer-level routing, hybrid configurations using a combination of conventional point-to-point radio and ad hoc networking when required, and dynamic master–slave topologies.

ISSUES

Mobile ad-hoc network routing protocols are designed to run on non-engineered, dynamic wireless networks. As a result, there are a number of issues in how to provide security and guarantee performance within the bandwidth, battery, processing, and memory constraints of mobile nodes communicating over radio links. These have to be addressed if MANets are to become commonplace.

Performance

Wireless Links: Relatively speaking, wireless links perform poorly compared to their wired counterparts. Their limited bandwidth and propagation problems, such as multipath fading, have a direct impact on routing and quality of service aspects, specifically latency, which is critical for applications such as voice. These links must function within the power constraints of the mobile nodes. Robust, low-power wireless links are essential. [**302,307**]

Routing and Scalability: A routing protocol must maintain security and quality of service in a dynamic environment but function within the limits of the link bandwidth (constantly changing) and node battery life, processing ability, and memory capacity. As ad hoc networks grow beyond a few nodes, this becomes increasing difficult. Current routing protocols provide only a fair ability to add nodes (scalability). Networks with poor scalability may lose the ability to provide the data bandwidths required for voice, have increased latency (delay) affecting the ability to talk over a link, or suffer reduced battery life. [**135,136**] Experimental results show that the throughput per node drops by a factor of 10 if the network grows from 2 to 8 nodes. [**307**] As more nodes join the network, the total data bandwidth of the system increases until the maximum that can be supported is reached. This increase is because nodes must transmit their own user’s voice and data, but also be able to relay signals from other users. Once the maximum is reached the total rate remains fairly constant as more nodes join. Because the total data transfer cannot exceed the maximum, the data rate per node must drop as more nodes are added. Poor scalability can also lead to reduced battery life as complex routing algorithms require more complex, high-power consumption processors, Wireless links operating at full rate also require more power. Finally, if the routing algorithms are not optimized for voice properly, they may cause such delays (latency) that it is difficult to talk.

Dynamic Location Modeling: In a large building fire, it is likely that one or more nodes or group of nodes will be unable to communicate with any other node or group of nodes because the node (the firefighter and his radio) are out of range, thereby losing communications with radios on the outside of the building. For this reason, it is important to understand the dynamics of where these nodes would be located during a fire. In addition, this requirement will be key in determining a methodology for the use of fixed routing devices that would be strategically placed by the firefighter. The location distribution should be analyzed for several major building types, and this overlaid on a propagation model to determine the system-level constraints. [**247**]

Security

The two key security considerations for mobile ad hoc networks are (1) tampering or utilization of techniques to intentionally render the system inoperable, and (2) eavesdropping and surveillance. Security becomes a difficult issue in a system such as this, since the nodes are mobile and can be connected dynamically in an arbitrary and random manner. It is possible that an outside mobile device could be able to disrupt a network where each member has autonomous capability and control. There are also physical security risks compared to static operation networks because portable devices may be stolen.

RECOMMENDATIONS

Research should be undertaken to determine the requirements and deployment guidelines for fixed MANet node deployment.

Firefighter requirements for routing, scalability, and security should be established and coordinated through organizations such as PSWAC or Project MESA.

Channel Coding, Interleaving, and Encryption

An important aspect of radio communications under impaired conditions is known as Forward error correction (FEC) or channel coding. Channel coding uses mathematical techniques of digital signal processing to enhance data reliability by applying redundancy in a known structure to a sequence of data before its transmission. While FEC is nearly always used in conjunction with various complementary modulations schemes (e.g. TDMA, CDMA, UWB), it is an independent element in the communication chain. The structure used by the FEC allows a receiver to detect (and an increased chance to correct) errors. The decoder corrects errors without requesting retransmission of the original information as is done in many acknowledgements-based protocols; hence the word *forward*. However, FEC comes at a price. The additional structure or redundancy in the data stream results in an increase in the required transmission rate.

TECHNOLOGY DESCRIPTION

Early advances in channel coding date back to Shannon in 1948 when he first published his concept of block coding or algebraic coding. Block coding is one of the simplest forms of FEC, where the coder inserts redundant bits in accordance with a specific algebraic algorithm. Several years later, convolutional coding was introduced which used a similar technique to block coding, but instead operated on the data in a continuous fashion instead of discrete blocks. In the late 1960s, Andrew Viterbi developed a coding scheme that bears his name and is now the most prevalent technique in use today. Viterbi FEC uses a probabilistic technique of considering memory and determining the most likely sequence of bits. Other techniques combine a variety of coding techniques to achieve improved performance. For example, while convolutional or Viterbi performs well with random errors, other techniques may handle burst errors that are typical in radio communication channels. This technique is termed *concatenated coding*. Another technique called Reed-Solomon coding is commonly used behind a Viterbi FEC to form a concatenated codec. [**333**]

Another technique that is frequently used in conjunction with FEC is interleaving. Interleaving is particularly effective in communication channels with burst errors. In virtually all digital communication channels, data are transmitted in a formatted frame or packet. These frames contain various fields such as an address or header, control words, and the actual traffic or payload data. In order for these frames to be properly detected, a synchronization method usually uses some predetermined sequence often referred to as a unique word. If this sequence is not properly detected, then the entire frame or burst of data could be lost. Also, certain protocols are more vulnerable to corruption of the control data and other critical fields that may occur when a burst error is encountered. Often a burst error in the wrong location of a frame will result in synchronization loss, and the receiver may require some time to regain synchronization, in which case a significant data loss may occur. [**333**]

In addition to the inherent synchronization associated with standard digital data transmission, the encryption required for secure communication also poses a challenging problem. In many modern encryptions, a “crypto sync” is maintained in the decoders. If this crypto sync is lost, it may be seconds before the secure channel is reestablished.

Interleaver technology mitigates this problem by effectively spreading the data over a larger period of time. This has the effect of being able to deal with the correction of Gaussian-like errors as opposed to the total data loss associated with burst errors. With this technique, a burst error on the radio channel may appear as random errors to the FEC algorithm. [**333**]

In the early 1990s, a new coding scheme called *turbo coding* was developed in Europe. [**334**] Turbo coding is the most advanced channel-coding scheme developed, and its performance approaches the theoretical limit suggested by Shannon. It is a technique that uses a combination of other techniques, with multiple encoders and an internal interleaver as an integral part of the coding scheme. The major drawback of turbo coding is that is it computationally expensive. As a result, custom hardware was required to use this technology in systems, as opposed to Viterbi and other techniques that were readily capable of being implemented on the same DSP as the modem functions. This factor combined with the establishment of a standard for turbo coding and complex intellectual property and licensing issues have slowed the widespread use of turbo coding. However, an ever-increasing number of systems are being implemented with turbo coding. [**323**]

FEC techniques are critical to improving radio communications. This technology is particularly important for radio communications inside buildings as it will allow more reliable links in these structures. In addition, as spectrum utilization becomes more of an issue, more advanced coding schemes can maintain channel efficiency.

APPLICATIONS

These techniques are commonly used in virtually all digital wireless communications. These include satellite, microwave, and radio communications. These are also used in many data storage systems, and even music CDs, to improve reliability of the storage mediums should the data become corrupted.

RESEARCH

Continuous work is being done in this area to improve turbo coding and other interleaving technology. Much effort has been spent on computation reduction and practical implementation techniques. New interleaving technology is also being developed to work better with higher level protocols, such as IP and ATM.

ISSUES

The major issue is assurance that the appropriate channel coding is used in the selected systems.

RECOMMENDATIONS

Further understand the operation of various FEC and interleaving schemes as they relate to the channel error characterization of transmissions inside buildings.

Investigate the implication of various coding schemes with other suggested areas such as MANets and UWB.

Power Line Communications

Power line communications (PLC), also referred to as broadband power line (BPL) uses existing power transmission networks to deliver communication services to any device plugged into an ac outlet and equipped with a PLC LAN interface. Using the power lines for communications is not a new concept. In the 1920s, AT&T was awarded PLC patents. In the 1950s, power utilities were using low frequencies (sub 1 kHz) to send control messages to equipment on the power grid. By the 1980s, bi-directional communications in the 5-to-500-kHz band were being used. Following these narrowband, low-data-rate PLC applications, broadband PLC started to develop and today commercialized products for LAN applications and Internet access are becoming more widely deployed. [**265**]

Firefighter use of PLC has several attractive benefits. It promises to be low cost because it uses existing infrastructure that is available in every building. Commercial developments in this technology area appear to be growing, and firefighters should derive cost benefits from this as well. But perhaps the biggest attraction to this type of communication is the ubiquity of power outlets. Not only are they found in every large structure, ac outlets are found in essentially every room, parking garage, and hallway. PLC data rates are sufficient for high-speed LAN applications including voice over IP and can be interfaced to the Internet.

TECHNOLOGY DESCRIPTION

Power line communications can be divided into two independent systems, in-house PLC and Access PLC. In-house PLC conforms to the HomePlug 1.0 standard for LANs and operates on the low-voltage (LV) power lines in buildings. Access PLC, where available, can be used instead of DSL or cable for backhaul of HomePlug traffic over the medium voltage (MV) transmission lines to the Internet. HomePlug is the only power line protocol in use for broadband LANs in homes and offices. On the MV transmission grid, however, many different protocols are in use for Access PLC with little effort being expended to develop a single standard.

Access PLC, currently in field trials with several power utilities, provides 45-Mbps rates over the MV power grid plus the low-voltage lines between the transformer and the electric meters of the premises connected to the transformer. The MV distribution network extends from the power distribution substation to the stepdown transformer. Some Access PLC systems have signaling that can pass through the transformer while others use a bypass technique. Typically, the bypass is accomplished by wireless or fiber optic connection as the utilities will not allow the LV lines any potential electrical connection to the MV grid for safety reasons. An Access PLC base unit is used to connect the Internet to the medium voltage line using inductive coupling rather than a direct connection. [**248**]

The LV power lines extend from the stepdown transformer into the home or office. Several protocols are used for low-voltage PLC. Most of the protocols such as X–10, CEBus, and LonWorks are meant for home and office automation and security applications and are not sufficient for high-data-rate applications. HomePlug technology is meant for high-speed LAN applications with current technology built to the HomePlug 1.0 standard [**294**] supporting data rates up to 14 Mbps, which is more than adequate for voice. HomePlug 1.0 data rates are compared with other broadband LAN types in Table 9. HomePlug is able to coexist on the same power lines with the other standards because it uses a different frequency band.

TABLE 9: NETWORK DATA RATE COMPARISON

Network Type	Data Rate (Mbps)
Ethernet/IEEE 802.3	10/100
IEEE 802.11a	55
HomePlug 1.0	14
IEEE 802.11b	11
HomePNA 2.0	10

Source: [**294**]

HomePlug LAN Internet access is accomplished by having a gateway via cable, DSL, wireless, or router. An alternative is to use a PLC modem to couple the HomePlug LAN to the Access PLC backhaul network. The modem is connected to the HomePlug LAN inside of the meter, and is connected to the electric line outside of the meter. By emerging standards, there is a frequency separation between Access and in-house: Access is to use the RF frequency space below about 10 MHz, while HomePlug should use the RF frequency space from 10 to 20 MHz.

Within a given HomePlug LAN, the network is self-configuring. The protocol supports devices joining or leaving the network at any time. If you plug in another module (ordinary node or gateway), then the network need only know how to address the node within the address space of the HomePlug LAN. A unique address must be set using a computer on the LAN or manually prior to inserting the device into an ac outlet. The addresses available on the network need to be known so as not use an address already in existence. If the address is not set manually, but by means of a computer, then the computer would need the information of the address space in the HomePlug LAN. The protocol included priority access with the intention of supporting high-date-rate and low-latency applications such as voice and video. The standard calls for the range to be up to 1,000 feet with throughputs as high as 14 Mbps. Real-world throughput is slower as shown in Table 10.

TABLE 10: EXAMPLE REAL-WORLD POWERLINE DATA THROUGHPUT

Transmitter	Receiver	Distance Between Transmitter and Receiver (ft)	Powerline	
			WSFTP Throughput (Mbps)	TTCP Throughput (Mbps)
Laptop (Dining Room)	Laptop 2 (Dining Room)	~2	4.2	5.2
Laptop 1 (Den)	Laptop 2 (Dining Room)	~23	4.5	5.3
Laptop 2 (Office)	Laptop 1 (Kitchen)	~35	4.0	4.5
Laptop 1 (Kitchen)	Laptop 2 (Office)	~35	3.1	3.1
Laptop 1 (Children's Room)	Laptop 2 (Office)	~70	1.9	1.8
Laptop 2 (Office)	Laptop 1 (Children's Room)	~70	4.1	3.9
Laptop 1 (Swimming Pool)	Laptop 2 (Office)	~60	2.0	1.6
Laptop 2 (Office)	Laptop 1 (Swimming Pool)	~60	2.4	2.8

Source: [**294**]

APPLICATIONS

This technique could be used analogously to the standard RF bi-directional amplifier approach that normally uses leaky feeder or coax and antennas for interior RF distribution.

Communications and Networking

A variety of HomePlug devices are widely available in retail stores for setting up LANs in homes and offices. Siemens, for example, sells devices that provide interfaces to the power line including:

- Wireless access point (IEEE802.11b) interface to HomePlug. Siemens sells this device to extend the range of a wireless network — an application very similar to what firefighters would like to do, extend the range of their hand-held radios.
- Wireless router to HomePlug.
- Wired router to HomePlug.

These devices and the HomePlug standard are designed to make setup easy for the average consumer. According to product literature, it is possible to merely connect the devices to an ac outlet and have a working network; Siemens ships all its HomePlug products with the same default key for its built-in 56-bit DES encryption. These units are inexpensive with prices for devices in the $100 range. Access PLC is still in the field trial stage, and prospects for commercial success of this technology remain uncertain.

The use of HomePlug LANs alone or in conjunction with Access PLC in homes and offices offers some possible applications for firefighters, including "intelligent buildings" and voice and video applications. A HomePlug LAN-equipped intelligent building has the potential to connect every electrical device to the LAN and in conjunction with Access PLC or alternatives in the same manner as DSL or cable modems connect to the Internet. This would allow firefighters to monitor HomePlug sensors (fire, smoke, and seismic could be developed) in buildings for fire location and progress and building stability before and after entering a burning structure. This ability could aid in developing firefighting plans and enhancing the safety of firefighters. It would even be possible to integrate this sensor data with fire prediction tools such as the Fire Dynamics Simulator and Smokeview visual tool under development by NIST. Even if firefighters did not have access to the intelligent building HomePlug LAN over the internet it may be possible to develop a first responder interface to a building's HomePlug LAN (or LANs) that firefighters could connect to when arriving at the fire scene.

A HomePlug LAN can also carry voice communications using voice over IP. In this application, the power lines could serve as range extenders for a new generation of radios such as the IEEE 802.11 mobile ad hoc network radios being demonstrated by NIST on its first responder test bed [**189**]. As firefighters enter a building, they would plug HomePlug to radio interface devices such as Siemens WAP/HomePlug into ac outlets as required to give radio coverage local to the HomePlug device. The HomePlug devices autonomously establish a network as long as they have been preset to use the same DES encryption key. When a firefighter communicates, his voice would be carried in multiple hops either directly to the outside of the structure or if necessary to the WAP/HomePlug interface then over the ac power lines to other WAP/HomePlug devices in range of the fire personnel outside of the building. [**217,250**] Firefighters would also need a radio device to enable firefighters using 802.11 radios to communicate with personnel using the traditional UHF and VHF radios outside the building. Motorola's ACU–1000 is a product that provides a similar type of interoperability for currently deployed radio systems that cannot interface directly. [**2**]

Another less likely option would be to inductively couple an Access PLC network base unit on the stepdown transformer side of the building's electrical meters. This approach has drawbacks. No devices such as those available for HomePlug are being developed, as this standard is intended as Internet backhaul rather than LAN applications. There are no standards for Access PLC, and two Access PLC networks cannot coexist, so firefighters could not set up their own network if one already existed. [**248**] Access PLC can coexist with HomePlug as each resides in a different frequency band. If Access PLC is used for Internet access, a conditioning unit will be installed in front of the electric meter. This unit has two outputs. The first output is the electrical line for the building, which passes through a low-pass filter to filter the Access PLC signal from the electrical lines entering the house. The second is the output for the PCL modem, which passes through a high-pass filter to allow only the high-frequency PLC signaling to the PLC modem.

RESEARCH AND PRODUCT STATUS

The HomePlug 1.0 standard is fully developed and devices built to this standard are widely available in retail stores. These products provide every conceivable type of network functionality likely to be needed in a LAN.

The next-generation standard (HomePlug AV) will produce data rates above 100 Mbps to support high-definition television (HDTV) and standard-definition television (SDTV). The HomePlug AV standard release is expected in late 2004 or early 2005.

Access PLC has reached the field trial stage. [**248**] Some of the companies involved in field trials of proprietary protocols are Ambient, Amperion, Current Technologies, and Main.net. A typical example of the many trials is one testing Ambient Corporation's PLC solution operating in Santiago since March 2002. This trial, in which a group of volunteers has broadband Internet access and voice over IP service, is in a high-standard commercial neighborhood in Santiago. This trial uses the power distribution grid operated by Chilectra, an electric utility for broadband Internet access. Internet access data transmission rates reach up to symmetric up/down 10 Mbps to the customer premise.

ISSUES

PLC has both technical and regulatory issues both for commercial applications and for firefighter applications.

Technical

Using an Access PLC Network: Only one Access PLC network can exist on a power line at a time, but several Access PLC protocols are being tested with no sign of a movement to standardize. Firefighters will not know which, if any, Access PLC standard is in use or which buildings or parts of dwellings have PLC modems installed. Further, no devices are developing applications such as interfacing wireless to power line.

Coexisting With or Joining a HomePlug: It needs to be confirmed that firefighter-installed HomePlug devices will operate as needed.

Setup and Use of a Firefighter PLC Network: It is not clear that the setup and operation of a PLC or PLC and wireless hybrid network, HomePlug or Access, can be made fast and straightforward enough for firefighters to accomplish in the limited time available to them on scene. A procedure would need to be established so firefighters know where to install HomePlug devices to relay voice over the power lines. An interface from the IEEE802.11 network to the firefighter's UHF and VHF radios would need to be developed to allow the new radios to communicate with the older systems in use.

Reliability: A test in 500 homes showed that 80 percent of outlet pairs supported more than 5 Mbps, and 98 percent were able to support more than 1 Mbps. [**294**] No testing was found in the literature search for real-world performance in structures other than homes. Two issues arise here: whether these results meet firefighter requirements and if these results hold true in wider testing, including office buildings and multidwelling units.

Security: At least in concept, a technique could be developed to let firefighters access a building's PLC network, but this could create security issues for the everyday users of these networks.

Range: It is unclear whether the real-world range and data bandwidth are sufficient for application to structures other than homes. A related concern is the range between devices installed on separate low-voltage ac lines connected to separate electrical meters. The meters may provide some low-pass filtering and attenuate the signaling.

Regulatory

Although the FCC is strongly supporting finding competing technologies (facilities-based competition) that provide communications services to homes and offices via a "third wire," opposition exists to Access PLC implementation. Access PLC uses the HF spectrum and has the potential to interfere with amateur radio, AM radio, military communications, radio astronomy, and distress frequencies. [**265**] The American Amateur Radio League is fighting Access PLC because of their concern that widespread implementation of Access PLC will interfere with the HF band and prevent reliable HF communications. [**257**] There is also some concern about interfering with differential GPS networks. [**261**]

RECOMMENDATIONS

A detailed study should be undertaken to determine the feasibility of using the HomePlug standard as an in-building repeater approach in large structures including those with electrical service via multiple electrical meters. Research is needed to determine what modifications are necessary to make HomePlug devices suitable for fire service communications and to determine if the distribution of ac outlets that work on the network is satisfactory.

Access PLC should be given a very low priority for use in firefighter applications due to the numerous uncertainties.

RF Distribution in Buildings Using Heating and Ventilation Ducts

Work has been done evaluating the feasibility of a technique for in-building RF distribution that uses heating, ventilation, and air conditioner (HVAC) ducts as waveguides. [**164**]

TECHNOLOGY DESCRIPTION

HVAC ducts in several configurations were used as waveguides for RF distribution. Depending on the frequency, good results were obtained with HVAC ducts and showed significantly lower losses than both direct propagation and leaky feeder cable techniques. Because an existing infrastructure is used, this approach has the potential to be low cost.

APPLICATIONS

This technique could be used analogously to the standard RF bi-directional amplifier approach that normally uses leaky feeder or coax and antennas for interior RF distribution.

One scenario for deploying an HVAC RF distribution system involves coupling RF into the ducts at a central point in the duct system. This could be near the central air handler in a typical HVAC installation. The coax to waveguide couplers, similar to those now used to couple to conventional waveguide, would be inserted into the duct. The RF would propagate via the duct, splitting at each branch or tee, which acts as waveguide power dividers. If RF obstructions are in the duct, the signal would be coupled around and special louvers would be installed in each room to radiate the signal. If the area to be covered was shielded from the duct then couplers could be used to feed a passive reradiator. Table 11 gives the duct sizes required for various bands.

TABLE 11: HVAC DUCT SIZE REQUIREMENTS TO SUPPORT COMMON WIRELESS BANDS

Band	Lowest Frequency (MHz)	Minimum Duct Width (rectangular) (cm)	Minimum Duct Radius (circular) (cm)
Cellular	824	18.20	10.70
ISM	902	16.60	9.75
PCS	1805	8.10	4.75
ISM	2400	6.25	3.66
U-NII	5150	2.91	1.71

Source: [**164**]

RESEARCH

Although providing in-building coverage for RF communications is an area of intense study, this technique is not being widely investigated, no buildings have been built or retrofitted to use this approach, and no commercial products are available. This is not a technique that can be adopted by firefighters prior to commercial companies using it as it requires the HVAC system to be specially built. If it were adopted in the future by companies providing commercial communications services (cellular, trunking, and PCS) it may be advantageous for firefighters to have equipment and the training to enable them to communicate via the building's built-in system.

ISSUES

Considerable research would be needed to go beyond the current technical feasibility study stage. Also, the business case for this type of application has not been put forth beyond the researchers feeling that using or reusing parts of existing infrastructures (HVAC ducts, etc.) should compare favorably with installation of leaky feeder and other current methods on in-building RF distribution.

Areas for further study include: [**164**]

- The waveguide characteristics of most HVAC ducts lead to multimode propagation. Added to this will be the effects of reflections from end caps, bends and junctions leading to delay spread. Delay spread and coherence bandwidth in this environment have not yet been developed.
- Efficient couplers for getting RF signals into and out of HVAC ducts have not been developed.
- Ducts are not manufactured as precision waveguides. Because of this, mode conversion from the dominant duct waveguide mode to orthogonally polarized modes is likely to occur at joints and other imperfections leading to signal loss.
- Viable methods of controlling and determining power splitting at branches and tees to allow proper system design do not exist.
- Current implementations of air dampers and fins in HVAC systems are likely to block RF signals propagating in the duct. New methods and materials that will

allow RF propagation while performing the necessary air handling have not been determined.
- Many HVAC systems contain RF obstructions such as fans and coils. Methods for coupling around these obstructions have not been investigated.

RECOMMENDATIONS

Further work should be supported to determine if an approach to providing BDA-type functionality is feasible. This work should include a study of the distribution of ductwork types in structures as well as research that addresses identified issues. Carnegie Mellon University has performed some of this research, but this area needs to be more fully explored.

Alternative Frequency Bands

It may be feasible to take advantage of the propagation characteristics of frequency bands outside of the normal VHF and UHF bands used in firefighter communications. The VLF and MF bands both provide improved propagation through earth (and by extension, building materials). The MF frequencies have been shown to efficiently couple to and propagate in mine tunnels over phone lines, ac lines, or even rails used for haulage vehicles to provide underground communications over distances of several thousand feet.

TECHNOLOGY DESCRIPTION

Very Low Frequency Communications

The VLF band is very narrow, only 27 kHz, and currently allocated for uses such as radio navigation. Radio waves in segments of this band can propagate long distances by the surface wave phenomenon, and the band is able to penetrate better into the ground than higher frequencies. [**311**] Voice communications in the VLF band would require the use of digital compression because of the limited bandwidth.

Medium Frequency Communications

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. Maritime and mobile distress, safety, and calling channels for public safety are allocated several hundred kHz 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). MF signals can propagate through solid material, even several hundred meters of rock under the proper conditions, do not attenuate as rapidly as higher frequencies when propagating around corners, and can propagate in conductive materials in the tunnels such as telephone and power lines. A widely available commercial application of MF is RF communications on power lines where it is used for LANs and marketed under the HomePlug name. The HomePlug application was discussed in the "Power Line Communications" section.

The U.S. Bureau of Mines and others [**17,18,19,20,21,22,23,24**] have studied MF propagation in mines in the United States, Canada, Australia, the United Kingdom, New Zealand, China, and South Africa. [**115**] These studies were able to measure and analyze the various RF propagation modes found in mines. The studies found that complex interactions occurred between MF radio waves and the environment as determined by the natural geology (rock composition, water content, etc.) and the man-made features (tunnel cross section, presence of conductors such as ac power lines, etc.). Of most interest to this report was the finding that when conductors, such as phone or power lines, were present propagation in the conductors (two or more conductors are required) completely dominates other underground propagation modes. [**288**] The studies found that, in effect, the existing conductors in the facility act as the antenna and transmission line for the communications system.

Mining organizations and related government organizations have also conducted field trials of systems using inductive coupling of MF waves into and reradiating from existing conductors such as phone lines and ac power lines to provide communications between a base unit and mobiles in underground mines over distances exceeding 4,700 meters without repeaters. [**204**] In these installations, it was found that the attenuation rate in the conductor was 1 dB/1,000 feet at 100 kHz and 3 dB/1,000 feet at 300 kHz; at 450 MHz, the rate was 21 dB/1,000 feet of leaky feeder cable. [**115**] Others have developed propagation models for frequencies from MF to UHF based on extensive measurements done in many underground mines. [**115,213**] These low-loss propagation modes exist in circular and rectangular air-filled tunnels with containing conductors (ac power and telephone lines and rail tracks). The attenuation is dependent on the distance between the conductors and the tunnel rock wall. [**211**]

The various MF communication installations used a number of approaches to antenna design. The designers had to make the antennas man-portable for the mobile radios. For the base station, the antennas could be larger as long as they fit within the tunnel dimensions. In either case, the antennas were much smaller than design rules would dictate for this frequency. Typically, antennas have dimensions on the order of one-half the signal wavelength, which for a 100 KHz signal would be 1500 meters, and obviously not practical. The man-portable radio typically used a loop antenna carried over the shoulder similar to a bandoleer [**116,175**] or integrated into a vest. [**204**] In one case [**127**] the base units used loop antennas that were 6 feet by 24 feet mounted along the tunnel wall, and in others used a single-line coupler placed around a bundle of phone lines similar to a current probe [**204**]. The portable antenna and both base station configurations performed well.

APPLICATIONS

Most products and research using VLF and MF frequencies are aimed at underground mining operations.

Very Low Frequency

VLF products have been introduced and are used as through-the-earth (TTE) emergency evacuation paging systems in place of stench gas [**115,179**]. Examples are Mine Site Technologies' PED system and MRS' FlexAlert system. [**180**] Both systems use large loop antennas to transmit to man-portable LF receivers. The man-portable systems typically build a VLF receiver and antenna into a miner's vest. These types of emergency paging systems may be of use to firefighters, especially in structures where typical VHF or UHF radios provide inadequate coverage.

Transtek has tested, but not commercially deployed, a VLF TTE communications system that allows two-way, real-time, voice communications. No published information is available on this system.

Medium Frequency

For communication applications, the predominant use of the MF is in underground mines, although in the 1970s fire departments in England used large MF loop antennas surrounding tall buildings to communicate with firefighters within the building. [**115**]

The mine communication applications made use of propagation via the conductor transmission lines in tunnels and direct wireless radio-to-radio communications. A typical setup had a base station that provided an interface to the telephone system used at the mine and an MF loop antenna or line coupler. The telephone system provided communications with the outside world while the loop antenna provided communications with the underground areas of the mine. The loop antenna was hung on the tunnel wall where it parasitically coupled with the conductors (telephone, ac power, rail tracks) running through the mine. If the line coupler approach was used, it was clamped around a bundle of conductors, frequently telephone lines. Portable transceivers were mounted in vehicles or fitted into vests worn by miners. Loop antennas for the portable units were worn bandolier fashion. Repeaters were installed in the mine. These units coupled to the conductor transmission lines carrying the MF communications signal. If a miner wanted to talk to another miner, the communications was direct; communication was wireless to the other miner's radio if he was local. If the other miner was out of direct wireless range, the repeater coupled the miner's transmission onto the conductor and a repeater near the other miner retransmitted it. Miners could receive transmission from base unit via the conductor without a repeater as long as they were within 2 or 3 miles of the base unit and were standing within about 2 meters of the conductors. [**211**] They could also talk back to the base station over the same conditions.

RESEARCH AND PRODUCT STATUS

There appears to be very little current research or development in the area of MF communications. Australia's Commonwealth Scientific and Industrial Research Organisation has some activity in this area but generally it is a mix of public and private funding and information dissemination is limited. [**17,18,19,21,22**]

ISSUES

Mine Communications Applicability to Above-Ground Structures

The research and trials in this area have been done in underground mines where MF waves propagate in either of two modes: using conductor pairs in tunnels as transmission lines for long distance communications or via direct, wireless radio-to-radio communications for shorter range communications. [**288**] The conductor-pair transmission line propagation uses the tunnel as part of the transmission media; this type of propagation may not occur in structures. To determine the practicality of direct, totally wireless radio-to-radio and power-line-coupled MF to radio, a measurement program needs to be designed and implemented that tests performance over a range of structure configurations.

Frequency Allocations

There are frequencies in the MF band for maritime and mobile distress channels for public safety use but not for MF structure communications. Also, there are potential interference problems between this and Access PLC or HomePlug networks.

Commercial Development

Based on the literature search, it appears little research or product development is ongoing in this area even for underground mining. This may make development time and cost prohibitive.

RECOMMENDATIONS

A study should be undertaken to determine the system design and effectiveness of a VLF or MF emergency evacuation paging system for firefighter application in structures.

Mine research used a conductor-in-tunnel waveguide. The applicability of this situation to structures should be investigated with empirical measurements in a range of structures and variety of conductors (power line, telephone, with and without direct coupling to conductors). All types of construction should be investigated, ranging from older buildings with predominantly load-bearing masonry walls to modern structures.

Man-portable and vehicular-mounted antenna development should be supported particularly as it addresses firefighting requirements.

Frequency allocation issues should be studied to determine the likelihood that this type of application would be approved.

Electronic Status and Firefighter Location

Firefighter status boards that require firefighters to manually check in and out are in use today. These systems, however, are prone to human error and can result in placing a firefighter's safety at risk when not used properly. Recently, systems have been tested that automatically track firefighter status to address the difficulties faced by incident commanders in tracking personnel on the fireground.

TECHNOLOGY DESCRIPTION

One system, the Motorola Fireground Accountability System [**185**], uses the wireless signals from each firefighter radio to automatically identify firefighters by sector or working assignment. Each radio channel corresponds to an incident command sector, and identification information is automatically shown on the incident commander's laptop. This reduces the manual approach to status tracking, although the system still has to be set up to assign radio channels to sector and enter firefighter identification information. Improvements to the system are planned. An evacuation tone triggered by the incident commander that wirelessly transmits an evacuation signal to firefighter radios will be available. Also, to be added is the capability to poll firefighter radios to identify radios that are out of coverage range. The time elapsed since the radio was in coverage will be logged. [**154**]

ISSUES

Although the system tracks radios to determine if they are out of coverage range and logs the elapsed time, it does not tell the incident commander the location of the firefighter.

RECOMMENDATIONS

Any automated personnel monitoring systems should be integrated with a radio location system to provide 3D location of either the firefighter's radio or an RF tag worn by the firefighter.

Radio location setup and operational requirements should be developed to make the location system operable by firefighters.

Bi-directional Amplifiers

Bi-directional amplifiers (BDAs) are a technically straightforward technique for providing improved coverage in areas that are shadowed from RF communications. Unfortunately, there are cost/economic barriers to implementation.

TECHNOLOGY DESCRIPTION

BDAs are used to boost an exterior signal reradiated in the interior of a structure or tunnel and boost the signal from the interior to the exterior. A typical installation uses an exterior antenna called a donor antenna to receive the RF communications signal from the exterior source (e.g., a public safety trunking system and transmit signal from the interior to the same trunking system). Attached to the donor antenna is a signal boosting unit, the BDA. This device uses one frequency band for the talk in channel and a second for the talk out channel. Attached to the BDA is a network of cables for distributing the signal throughout the structure. The network can be leaky feeder cable that radiates the RF signal along its entire length or can be standard coaxial transmission line that has antennas and hybrid couplers attached where needed to provide the desired coverage. Proper functioning of a BDA system requires a significant amount of RF engineering design prior to installation and a significant amount of test and rework time after the system is installed. BDAs will not work with simplex radios.

APPLICATIONS

Many companies provide the components (antennas, cable, etc.) and the engineering services needed to install BDA-type systems.

ISSUES

While technically straightforward to implement, a bi-directional amplifier system is expensive to install. It requires the installation of an exterior donor antenna, a bi-directional amplifier unit, and multiple interior antennas and hybrid couplers fed by long lengths of coaxial transmission line or, alternatively, the use of leaky feeder cable run throughout the building. This is expensive to install in new buildings and even more expensive to retrofit to existing buildings. Commercial cellular and trunk radio operators see no economic incentive for the installation of such a system except in very limited cases where they are guaranteed an income stream for a sufficient time. Systems that have been installed are not likely to have been designed with firefighter requirements in mind and may not provide the coverage desired or the redundancy needed to provide satisfactory operation while sustaining damage during a fire. One answer to this is to force installation by building code requirements. This has met with resistance from local governments who do not want to put disincentives to businesses into the building code.

RECOMMENDATIONS

Work with multiple local governments to establish regional adoption of building codes requiring installation of BDA systems in new high-rise buildings. The system requirements should address fail-safe features necessary to provide reliable communications even while sustaining fire damage.

Investigate alternative implementations of the BDA concept such as power line communications, medium frequency coupling to conductors, or use of modified HVAC ducts.

Smart Antennas

New-generation smart antennas may provide improved communications if integrated into firefighter repeaters, inside or outside a structure.

Smart antennas have been in limited use for commercial CDMA cellular and other wireless applications for several years. These smart antennas are installed at the base stations where technical personnel manually program the combining circuitry phase and gain adjustments to produce the desired antenna gain, beam-width, and direction to reduce interference. In a CDMA network, reducing interference increases capacity. In general, the antennas are not automatically adaptable to changes in the RF environment or adapted too slowly to react to fast changes. Antenna setup requires an understanding of RF propagation, and in-building coverage improvement is not addressed. The antennas also are not portable and are expensive.

TECHNOLOGY DESCRIPTION

A smart antenna consists of a set of antenna elements called an array connected to a combining circuit that adapts to the RF environment. The combining circuit adjusts the phase and gain of the each elements' signal and then sums the signals together. This signal is fed to the receiver. Recently, product plans have been announced that are directed at the wireless LAN market. These developments promise significant benefits for wireless LANs:

- Significant increase in wireless link range
- Increased network data throughput
- Reduced power consumption
- Higher reception reliability

In contrast to the smart antennas used in cellular base stations, these antennas are small and low cost enough to be integrated into home and office wireless access points. They have the ability to scan for signals coming from other wireless access points and mobile nodes and quickly adapt the smart antenna to point in the direction necessary to optimize the wireless link between the smart-antenna-equipped wireless access point and the mobile node or other wireless access point. The antenna pattern can be optimized to counter the effects of noise, interference, and multipath. [**313**] These antennas have multiple, independent antenna beams so they can produce multiple optimized antenna patterns to accommodate multiple wireless links simultaneously.

Another type of smart antenna is called a MIMO, or multiple input, multiple output, system. In a MIMO implementation, both the transmitting and the receiving radio use antenna arrays. These systems have demonstrated the potential for very high capacities. If the number of antennas is the same at the transmitter and the receiver, the link capacity increases linearly with the number of antennas. [**340**] These types of antennas have been tested for hand-held radios as well. [**339**] In this case, because of the proximity of the antenna array elements, pattern and polarization diversity was used in the MIMO processing.

APPLICATIONS

The inclusion of smart antenna technology in portable repeaters and wireless access points could bring important benefits to firefighters. This technology, combined with a MANet for firefighters or with conventional UHF or VHF portable radios, would provide improved range in or out of buildings. Firefighters could set up a smart-antenna-equipped repeater on the building's exterior and it would cover more of the interior. If the situation demanded, they could carry additional repeaters into the building that could communicate with the exterior repeater and the firefighter mobiles. One of the functions that could be designed into a smart antenna would be the ability to help the firefighter automatically locate a site for the repeater. It may be possible to design the smart-antenna-equipped repeater to guide firefighters in placing them for the best results. Because the smart antenna scans antenna beams to automatically optimize the wireless links to devices within its range, a firefighter could carry one into a building and by watching a simple display know if the signal strength back to the outside repeater is in the optimum range. Also, if firefighters deployed smart wireless access points through a building, they could use the same feature to know when they have reached the optimum distance from the last repeater.

Several companies have announced products in development. Lumera Corporation has demonstrated an antenna design using a patch array technology to form multibeam patterns. The company says the antenna, measuring about 3 inches on a side and 1/4 inch height, can support low-power applications such as IEEE 802.11 LANs, as well as applications that require up to 10 watts. [**321**] A second company, Airgo Networks Inc., is developing a cost-effective smart antenna based on an OFDM three-antenna, four-chip design. Airgo claims it can double the throughput and quadruple the range of 802.11 wireless LANs. [**322**]

RESEARCH AND PRODUCT STATUS

This is an area of active research and product development. Several companies have announced products, but these still seem to be some time away from actual product deployment. Also, Project MESA has identified smart antennas as an area of interest for enhancing public safety communications.

In general, the performance enhancements offered by the use of smart antennas in multihop ad hoc networks can be significant. Issues still remain due to the added complexity that smart antennas add to the protocols. [**313**]

ISSUES

The effectiveness of smart antennas is closely linked to media access control (MAC) protocols. Various MAC protocols have been explored for use with smart antennas. The optimum antenna pattern is not obvious due to MAC protocol complexity in conjunction with the functionality of multihop ad hoc networks. Until this is resolved, smart antennas may be of limited use.

RECOMMENDATIONS

Smart antennas improve wireless LAN performance including mitigating multipath and should be considered for incorporation into both traditional repeaters and wireless access points for a firefighter-deployed MANet.

Research is needed to develop protocols that optimize smart antenna performance in smart antenna applications. The MIMO architecture holds particular promise.

Training for the use of smart antennas or simplification of the setup procedures should be pursued if smart antennas are to be easily used.

Development of requirements for firefighter applications via an organization like Project MESA should be considered.

Spread Spectrum

The use of spread spectrum modulation techniques can provide significant multipath mitigation and result in improved communications within structures. [**218,219**]

TECHNOLOGY DESCRIPTION

The two main types of spread spectrum modulations are frequency hopping and direct sequence. A third type is a hybrid of both.

Direct sequence systems use a high-rate code sequence, along with the information being transmitted, to modulate their RF carrier. The high-speed sequence is used directly to modulate the carrier, setting the transmitted RF bandwidth. Binary code sequences from 11 bits to 2^{89}–1 bits have been employed, at code rates up to several hundred megabits per second. CDMA cellular systems used in the United States are an example of a direct sequence spread spectrum system.

A frequency hopping system covers a wideband frequency spectrum by hopping from frequency to frequency over a wide band. The sequence of frequencies occupied is determined by a code sequence, and the rate of hopping is a function of the information rate.

Advantages of spread spectrum include:

- Multipath mitigation
- Rejection of narrowband interference.
- Multipath access: number of users can access a common channel for communication.

- Random access: users can start their transmission at any arbitrary time.
- Privacy due to unknown pseudo random codes: The applied codes are, in principle, unknown to a hostile user. This means that it is difficult to detect and monitor the message of another user.

APPLICATIONS

The literature search found one non-UWB spread spectrum product intended for firefighter use, a frequency hopping two-way emergency pager called T PASS 3 Evacuate. [**197**] This device is an NFPA compliant two-way PASS device that operates in the unlicensed band from 90–928 MHz. It can individually address up to 1,100 firefighters or can page all at once. It has a companion repeater to provide extended range when necessary. In one field trial, two of the repeaters were required to provide coverage in a 75-story high rise. The pager is in use in the Las Vegas and Houston fire departments.

ISSUES

Even though spread spectrum signals are immune to most narrow band interfering signals they can be interfered with under the right circumstances. When the interferer is strong enough to overcome the processing gain from signal spreading, a narrow band interference suppression algorithm is needed. An example of this type of interference was interference caused by old analog cell phones to newer CDMA cell phone base stations.

RECOMMENDATIONS

New firefighter communications systems procurements should incorporate multipath mitigation as a basic requirement. Use of spread spectrum techniques with the ability to withstand narrow band interference is a key component in mitigating multipath.

Other Technologies

COMMERCIAL WIRELESS NETWORKS

Use of commercial cellular (800 MHz and 1900 MHz) radios were discussed at the preliminary project meeting and rated a low priority for inclusion in this report for the following reasons:

- Propagation in structures similar to or worse than existing firefighter UHF radios.
- Cellular network availability is not likely in emergencies either due to overuse or the system being down because of emergency.

PROJECT 25

Project 25, a joint effort of U.S. federal, state, and local government, is the approved narrowband interoperability voice and data standard for use in the 700 MHz band for public safety wireless communications. Project 25 radios were discussed at the preliminary project meeting and rated a very low priority for inclusion in this report for the following reasons:

- Project 25 standard radios share the same propagation limitations as other UHF radios.
- Project 25 is intended to address other issues such as interoperability and security rather than improving in-building communications.

BLUETOOTH

Bluetooth, a technology that is generally used to wirelessly connect devices, was also discussed at the preliminary project meeting and rated a low priority for inclusion in this report for the following reasons:

- Range limited to about 10 m.
- Data rate approximately 1 Mbps.
- Intended for short-range use to replace cables.

The literature search did not find anything to cause the priority of this technology to be raised as no applicable research or products were found relevant to this report's focus on firefighter communications in structures.

General Recommendations

The following recommendations are given in addition to the detailed recommendations by technology area given above. They are generally applicable to the problem of firefighter communications in structures.

The first set of general recommendations address critical deficiencies in the knowledge base of the propagation characteristics of radio waves in structures. The literature search revealed that while propagation studies have been performed on specific frequencies there has been no comprehensive study of propagation characteristics for the full frequency range of interest to fire and emergency communications. Nor is there a complete understanding of the effects of building materials on these propagation characteristics. This latter topic is one that should be ongoing as new materials and building techniques, especially those used in high-rise construction, are continually evolving.

*RF measurements by NIST [**78,79**] should be extended to cover from VLF to 10.6 GHz. Investigation of frequency dependency of the material dielectric and conductivity constants over these frequencies should also be funded.*

An RF propagation survey in structures from VLF to at least 10.6 GHz (upper end of band allowed for UWB) should be pursued.

The next set of recommendations address deficiencies that affect the determination of system specifications for structure communications. For example, 100 percent in-building communications coverage is not a realistically achievable goal; 30 percent coverage may currently be achieved and is insufficient. These guidelines and requirements need to be detailed so that system developers are aware of the acceptable performance parameters. Moreover, consideration must be given on how to merge new technology communication systems with existing fire department communication systems.

Requirements should be developed for the minimum level of coverage necessary for in-building communications. This is a basic requirement and is independent of the communications technology.

Guidelines for repeater placement for a variety of structures and fire scenarios should be developed.

New technology communications systems should be interoperable, to some degree, with legacy systems.

Current communications technology is a dynamic and evolving field. It is important that the technological community and communication system developers understand the needs of the fire service. Conversely, it is important the fire services understand the possibilities and the limitations of the technologies available. New systems will be more complex than the fire service has worked with in the past. Both the fire service and manufacturers will need to address the interface between user and developer.

Establish and fund an organization to facilitate dialog between emergency responders and the technical and regulatory groups.

Public workshops to address firefighter communications issues found in structures should be held on a routine basis.

A newsletter, electronic bulletin board, web page, or other information sharing means should be developed specific to firefighter communications issues.

Summary of Recommendations

Table 12 summarizes all of the detailed recommendations noted throughout this chapter. The recommendations are grouped by technology area.

TABLE 12: SUMMARY OF RECOMMENDATIONS

Technology Area	Recommendation	Page
Ultra Wideband	*The public safety community should develop a position in regards to supporting UWB deployment and the minimum requirements needed for each firefighter application. If the fire community's position is to support this technology, then minimum requirements should be developed for firefighter applications. An organization, such as PSWAC, NFPA, or Project MESA should be used to make the community's position known to the spectrum-regulating organizations.*	50
	The public safety community, using an organization such as PSWAC, NFPA, or Project MESA, should support antenna research and provide input on firefighter-specific antenna requirements.	50
	The public safety community, using an organization such as PSWAC, NFPA, or Project MESA, should support research and design of advanced receiver architectures such as the Rake receiver.	50
	Research into electromagnetic susceptibility and compatibility should be supported through organizations such as PSWAC, NFPA, or Project MESA. Ideally, power and frequency restrictions will be lessened to make UWB more widely applicable for public safety applications.	50
Mobile Area Networks	*Research should be undertaken to determine the requirements and deployment guidelines for fixed MANet node deployment.*	57
	Firefighter requirements for routing, scalability, and security should be established and coordinated through organizations such as PSWAC or Project MESA.	57
Channel Coding, Interleaving, and Encryption	*Further understand the operation of various FEC and interleaving schemes as they relate to the channel error characterization of transmissions inside buildings.*	59
	Investigate the implication of various coding schemes with other suggested areas such as MANets and UWB.	59
Power Line Communications	*A detailed study should be undertaken to determine the feasibility of using the HomePlug standard as an in-building repeater approach in large structures including those with electrical service via multiple electrical meters. Research is needed to determine what modifications are necessary to make HomePlug devices suitable for fire service communications and to determine if the distribution of ac outlets that work on the network is satisfactory.*	65
	Access PLC should be given a very low priority for use in firefighter applications due to the numerous uncertainties.	65

Technology Area	Recommendation	Page
RF Distribution in Buildings Using Heating and Ventilation Ducts	*Further work should be supported to determine if an approach to providing BDA-type functionality is feasible. This work should include a study of the distribution of ductwork types in structures as well as research that addresses identified issues. Carnegie Mellon University has performed some of this research, but this area needs to be more fully explored.*	67
Alternative Frequency Bands	*A study should be undertaken to determine the system design and effectiveness of a VLF or MF emergency evacuation paging system for firefighter application in structures.*	70
Alternative Frequency Bands	*Mine research used a conductor-in-tunnel waveguide. The applicability of this situation to structures should be investigated with empirical measurements in a range of structures and variety of conductors (power line, telephone, with and without direct coupling to conductors). All types of construction should be investigated, ranging from older buildings with predominantly load-bearing masonry walls to modern structures.*	70
Alternative Frequency Bands	*Man-portable and vehicular-mounted antenna development should be supported particularly as it addresses firefighting requirements.*	70
Alternative Frequency Bands	*Frequency allocation issues should be studied to determine the likelihood that this type of application would be approved.*	70
Electronic Status and Firefighter Location	*Any automated personnel monitoring systems should be integrated with a radio location system to provide 3D location of either the firefighter's radio or an RF tag worn by the firefighter.*	71
Electronic Status and Firefighter Location	*Radio location setup and operational requirements should be developed to make the location system operable by firefighters.*	71
Bi-directional Amplifiers	*Work with multiple local governments to establish regional adoption of building codes requiring installation of BDA systems in new high-rise buildings. The system requirements should address fail-safe features necessary to provide reliable communications even while sustaining fire damage.*	72
Bi-directional Amplifiers	*Investigate alternative implementations of the BDA concept such as power line communications, medium frequency coupling to conductors, or use of modified HVAC ducts.*	72

Technology Area	Recommendation	Page
Smart Antennas	*Smart antennas improve wireless LAN performance including mitigating multipath and should be considered for incorporation into both traditional repeaters and wireless access points for a firefighter-deployed MANet.*	75
	Research is needed to develop protocols that optimize smart antenna performance in smart antenna applications. The MIMO architecture holds particular promise.	75
	Training for the use of smart antennas or simplification of the setup procedures should be pursued if smart antennas are to be easily used.	75
	Development of requirements for firefighter applications via an organization like Project MESA should be considered.	75
Spread Spectrum	*New firefighter communications systems procurements should incorporate multipath mitigation as a basic requirement. Use of spread spectrum techniques with the ability to withstand narrow band interference is a key component in mitigating multipath.*	76
General Recommendations	*RF measurements by NIST [78,79] should be extended to cover from VLF to 10.6 GHz. Investigation of frequency dependency of the material dielectric and conductivity constants over these frequencies should also be funded.*	77
	An RF propagation survey in structures from VLF to at least 10.6 GHz (upper end of band allowed for UWB) should be pursued.	77
	Requirements should be developed for the minimum level of coverage necessary for in-building communications. This is a basic requirement and is independent of the communications technology.	78
	Guidelines for repeater placement for a variety of structures and fire scenarios should be developed.	78
	New technology communications systems should be interoperable, to some degree, with legacy systems.	78
	Establish and fund an organization to facilitate dialog between emergency responders and the technical and regulatory groups.	78
	Public workshops to address firefighter communications issues found in structures should be held on a routine basis.	78
	A newsletter, electronic bulletin board, web page, or other information sharing means should be developed specific to firefighter communications issues.	78

APPENDIX A: PRIORITIZED PROJECT ISSUES

Ranking	Area	Topic
10	Accountability (Integrating Personal Accountability Systems (PAS) with Communications)	• Integrating PAS with communications • Electronic accountability • Automatic vehicle location • Electronic command boards
10	Communication Planning and Coordination	• Through building (into/out of) • Underground • In building
10	Grants	• Small business grants – who and what (if information available)
10	Monitoring Firefighter Welfare and Location On-Scene	• Role/responsibility of dispatchers. • Use of field communications units and communications coordinators • Remote monitoring • Vital signs • Location
10	Reliability Issues	• Line-of-sight limitations • Underground (subways, parking garages) • Confined space rescue • Communication into and out of buildings (especially high-rises) • Intermittence • Communication coverage/dead spots
10	Reliability Issues – Interference	• Communicating into buildings • Radio propagation through fire, heat and smoke
10	Unsuitable Equipment	• Frequency band unsuitable for structure/ground penetration

Ranking	Area	Topic
2	Reliability Issues	• Equipment Failure • Mechanical/technical issues (unstable equipment, radio malfunction) • Concerns about reliability of 800-MHz digital systems • Failure observability • Field testing prior to implementation • Radios introduced into fire stations without field testing • Interference • Atmospheric • Electronic • Built environment (tunnels, high-rise buildings, shipboard) • Jamming (terrorism) • Reliability of 800 MHZ digital technology/reliability of Motorola XTS 3500R digital systems • Repeater performance/repeater infrastructure • Environmental (hills, foliage, mountainous terrain, distance) • Acknowledgement of message
2	Unsuitable Equipment	• Most equipment adapted from other uses • Unable to communicate from inside using full personal protective equipment
1	Communication Planning and Coordination	• Coordination of ground-to-ground and air-to-ground communications • Lack of integrated communication planning (frequency coordination) • Failure to use ICS correctly or at all • Inadequate ability to receive, disseminate, and analyze information • No backup data – command post destroyed as in World Trade Center • Vehicle/unit tracking – geo-location • Intra- and interagency communications
1	No Equipment	• Some firefighters lack radios

Ranking	Area	Topic
Not Investigated	Ergonomics	• Human factors receiving little attention • Develop additional skill sets • Stress-tempered communication skills • Survival simulator (similar to airline pilot virtual reality simulator) • Radio discipline • Cultural factors • Unwillingness to call for help • Inadequate training and personnel performance • Performance issues on complex multi-channel/multi-mode radio systems • New systems must be learnable/focus on learn-ability • Unfamiliarity with the use of new radio equipment • Ability to deploy and manage new technology • Resistance to new technology • Difficulty communicating while wearing SCBA • Current adaptations (speech ports, face piece integrated microphones, intercom systems, portable radio interfaces, throat mikes, bone mikes, etc) receive mixed reviews

Ranking	Area	Topic
Not Investigated	Inadequate System Capacity	• During complex, multi-alarm incidents with many operating units attempting to communicate • Number of frequencies available vs. number of people attempting to use those frequencies • Legal process to acquire • Lack of repeaters/repeating infrastructure • Opportunities to test and deploy portable, mobile, air-based and stationary repeaters • Portable radios needed for all firefighters • Should be considered a critical item of personal protective equipment akin to SCBA • Every firefighter (or two-person team) working in a hostile environment should have a portable radio with emergency distress feature • Radio spectrum deficiencies • Work at federal level to secure enough radio spectrum • Radio spectrum interoperability for public safety • Department of Defense report re. progress on 138-144-MHz band overdue • Commercial applications (e.g., Nextel) • Cell phones • System capacity • ACU1000 – mixer – multiple frequencies patched (IC only use)
Not Investigated	Unsuitable Equipment	• Firefighters must use SCBA and communicate effectively • Needed: a better portable radio specifically designed for the structural firefighting environment • Physically robust system • Waterproof • Ruggedized/shock resistant • Able to withstand high heat environment • Designed to be easily operable with heavy gloves in a hostile environment • Observability of LCD displays in low light conditions • Concerns over triggering radio controlled bombs and terrorist devices • Black box recorder • Battery life, interchangeability

APPENDIX B: FIRE DEPARTMENT COMMUNICATIONS – EXPERIENCES FROM THE FIELD

The information contained in this appendix was gathered from a variety of sources. Much of the information comes from fire department management studies previously undertaken by TriData Corporation. Some information comes from individual fire department annual reports, websites, or other fire department literature. Wherever possible, the information from these studies was verified with the fire department to ensure that the most current data was reflected in this report.

TABLE 1: EXPERIENCES FROM THE FIELD – DEPARTMENT OVERVIEW

Jurisdiction	Resident Population [13]	Land Area[1] (sq. mi)	Land Area Protected	Fire Department Type	Uniformed Employees	Communications System
Austin, TX	656,562	252	Urban	Career	979	UHF (450 MHz)
Bellingham, WA	67,171	32	Urban/ Suburban	Career	140	VHF
Boston, MA	589,141	48	Urban	Career	1,600	UHF (483-MHz Conventional)
Boulder, CO Rural Fire Department	18,000	25	Suburban/ Rural	Combination	8 FTE; 35 Volunteer	VHF (153–155-MHz)
Brighton, CO	20,905	17	Suburban/ Rural	Combination	9 FTE; 60 Volunteers	UHF (400/800 MHz Trunked)
Charlotte, NC	540,828	242	Urban	Career	890	UHF (800 MHz Trunked)
Chicago, IL	2,896,016	227	Urban	Career	4,000	VHF (Conventional)
Clark County, NV	1,375,675	8,000	Urban/ Rural	Combination	1,300 Career; 400 Volunteer[14]	UHF (800 MHz Trunked)
Dallas, TX	1,188,580	385	Urban	Career	1,700	UHF (400 MHz)
Detroit, MI	951,270	139	Urban	Career	1,296	UHF (400 MHz)
Everett, WA	91,488	48	Urban/ Suburban	Career	158	VHF
Fairfax County, VA	969,749	395	Urban/ Suburban	Combination	1,166	UHF (460/800 MHz Trunked))
Gettysburg, OH	3,700	60	Rural	Volunteer	50 Volunteers	VHF (154-MHz)
Los Angeles, CA	3,694,820	469	Urban	Career	3,200	UHF (800 MHz Conventional)
Milwaukee, WI	596,974	96	Urban	Career	1,100	UHF (400 MHz)
Phoenix, AZ	1,321,045	475	Urban	Career	1,366	UHF (Conventional)
Pittsburgh, PA	334,563	56	Urban	Career	896	UHF
Portland, OR	529,121	134	Urban	Career	680	UHF (800 MHz)
San Antonio, TX	1,144,646	412	Urban	Career	1,018	UHF (800 MHz Trunked)
San Diego, CA	1,223,400	324	Urban	Career	1,100	UHF (800 MHz)

[13] Data from U.S. Census 2000 was used for consistency and comparison. Data may not agree with that reported by the jurisdiction.
[14] Many fire departments that operate within Clark County, NV including but not limited to Las Vegas, North Las Vegas, Henderson, and the Clark County Fire Departments. These numbers are estimates, based on information gathered from department websites.

Jurisdiction	Resident Population[13]	Land Area[1] (sq. mi)	Land Area Protected	Fire Department Type	Uniformed Employees	Communications System
San Francisco, CA	776,773	49	Urban	Career	1,700	UHF (800 MHz)
Schaumburg, IL	75,386	19	Suburban	Career	138	UHF (800 MHz)
Springfield, NJ	14,429	5	Suburban	Combination	33 Career and Volunteer	UHF (470 MHz)
Wichita, KS	344,284	136	Urban	Career	371	UHF (800 MHz Trunked)

Austin, TX

The all-career Austin Fire Department (AFD) serves a population of 663,000. Its nearly 1,000 uniformed firefighters operate out of 39 fire stations strategically located throughout the department's 234-square-mile response area. That area includes portions of two neighboring counties (Travis and Williamson) as well as Austin-Bergstrom International Airport.[15]

Located in the Central Texas hill country, Austin is approximately 230 miles from Mexico and less than 200 miles from Dallas, Houston, and San Antonio. It is also the State Capital of Texas.

Its downtown area has high-rise buildings (8 – 10 of which are over 20 stories), below-grade structures such as tunnels (Capitol building), basements, and underground parking garages, and diverse terrain—all of which pose communication challenges. Austin is also home to many computer chip manufacturing plants.

For the past 15 years, radio communications have been spread over six radio channels on the 450 UHF band. One channel is designated for dispatch, while the other five are devoted to tactical operations. Channels are assigned geographically, and each channel has a repeater.

Communication problems are sometimes encountered by the fire department. Some are technical issues related to various structures (e.g., high-rise buildings, tunnels, concrete buildings, etc.) and others are related more to interoperability – where communications with other city departments or neighboring jurisdictions Is sometimes compromised. Overcapacity and training are not issues, as the department conducts training programs and employs standard operating procedures (SOPs).

To remedy the interoperability problem, the Austin's public safety agencies are upgrading to an 800-MHz trunked system. Reconfiguration to the 800 MHz is expected to solve the interoperability problem. The improvement in interference may be achieved through a modified system design and infrastructure and should improve other interference caused within structures, as well.

[15] Austin Fire Department Fact Sheet (www.ci.austin.tx.us/fire/fdfacts.htm.). Data may not agree with that reported by the U.S Census 2000.

Bellingham, WA

The Bellingham Fire Department (BFD) provides fire suppression as well as emergency medical services. Bellingham, Washington, is located in Whatcom County, which is the last county on the Washington coastline bordering British Columbia. Bellingham's full-time, career firefighters serve a population of approximately 78,000.[16] This includes citizens of Bellingham and some fire protection districts in unincorporated Whatcom County.

Bellingham is 90 miles north of Seattle and 50 miles south of Vancouver. To the east are the Cascade Mountains, and to the west is Puget Sound. The area covered by the BFD has a diverse topography with extremely mountainous areas to the east, and wide lowland floodplains near the marine shoreline. The BFD is the primary provider of emergency ambulance service throughout the county, and frequently responds to areas deep within the county where radio coverage is limited.

Currently, the BFD uses a VHF radio system with relatively good coverage of their response area. However, the department reports various "dead spots" within the city where firefighters cannot communicate with dispatch or with one another. There is one particularly troublesome spot—a large mall in the City where firefighters cannot communicate using their portable radios and where pagers will not activate. For all incidents above a second alarm, the BFD uses mutual aid companies from nearby jurisdictions. All of these companies are dispatched by the same communications center, which facilitates communications prior to and during incidents.

Like many departments, the BFD reports that communications from below grade are intermittent. In addition, communications with the Police Department are difficult, due to the lack of interoperability between the two agencies' radio systems.

With such close proximity to the Canadian border, there is a limit on the strength of the radio signals the BFD can use. A recent communications study for Whatcom County recommended transitioning all emergency service providers in the county to an 800 MHz system; the BFD is working with the county to identify possible sites for radio towers and repeaters. . In the interim, they are exploring the possibility of installing a repeater near the mall to improve communications in that part of the City. The Department also uses Nextel cellular phones. However, after an earthquake several years ago, they discovered that the radio system functioned, but the Nextel phones did not.

In addition, BFD personnel reported difficulty using portable radios while wearing PPE (personal protection equipment), particularly gloves. To address this problem during emergency incidents, all BFD radios are programmed so that the first and last positions on the frequency dial are the same and are a channel that is always monitored by dispatch. With this scheme, if a firefighter becomes trapped or disoriented, etc., and

[16] The population served differs from the resident population as report by the U.S. Census 2000 because the Bellingham Fire Department protects citizens in parts of unincorporated Whatcom County.

cannot communicate with units on the scene, he can always communicate with the dispatch center.

Boston, MA

The Boston Fire Department (BFD) is one of the oldest career fire departments in the United States. Its 1,600 firefighters serve in 35 stations, protecting 575,000 people spread over 47 square miles.[17]

The fire department operates a conventional UHF 483 conventional system. One channel is dedicated to dispatch and four channels are for fire operations (all with repeaters). Each channel operates in duplex mode. There are 20 satellite receivers strategically placed throughout the city to support communications. The system has additional capabilities for use in tunnels and underground areas; special receivers and transmitters are dedicated to subterranean communications.

Imperfections within the system design has led the department to upgrade or replace some of its communication system equipment – base stations, receivers, etc. Essentially the department now has a new infrastructure.

Prior to the upgrade, BFD was plagued with unwanted signals out of the system. Like other cities, Boston experiences dead spots in high-rise buildings and basement or sub-basement areas, as well as in some residential structures. The hilly terrain tends to cause dead spots in residential areas. To combat this problem, the BFD uses transmitter steering, which moves communications from one transmitter to another.

Communications in underground structures also presents a problem. For more than a decade, the City of Boston has been undergoing major transportation changes. The plan is to eliminate the Central Artery, an elevated six-lane highway that runs through the center of downtown, with an underground expressway directly beneath the existing road. This project is known as “The Big Dig.” This new tunnel will present considerable challenges to the public safety departments of Boston, including the fire department.

The walls of the tunnel create a man-made barrier to radio frequency signals that carry radio communications. In 1995, when the construction the Ted Williams Tunnel, which extends from Logan Airport to the Greater Boston area, was complete, the City implemented a state-of-the-art communication device (i.e. leaky cable) that could operate 31 channels simultaneously. The city installed a leaky cable running along the roof of the tunnel. A leaky cable is a “by-product of conventional coaxial cable with small slits cut through its layers that allow RF signal to seep out in amounts strong enough to cover small areas of square footage.” [**296**]

Many new buildings in Boston have bi-directional amplifiers incorporated within their structures. Bi-directional amplifiers, commonly known as BDAs, are used for

[17] Boston Fire Department Overview (www.cityofboston.gov/bfd/overview/overview.htm.). Data does not agree with U.S. Census residential population data.

improving/correcting portable radio communications to, from, and within (large) structures. These BDAs provide the fire department the ability to operate all four fire department channels within a building.

Interoperability is another serious issue in Boston. Boston is part of a metro fire district that includes 34 other cities and towns. The district lacks a system for direct communication with all of the other departments. When a major incident occurs, a BFD chief, acting as the incident commander, will be collocated with an incident commander from another department.

Boulder, CO Rural Fire Department

Boulder Rural Fire Department is located to the north of the City of Boulder in unincorporated Boulder County, Colorado. It protects a population of approximately 18,000, spread over 25 square miles. The region is suburban and rural, and includes mountains, heavily forested areas, as well as some light industrial areas.

The Boulder Rural Fire Department is a combination department, with volunteer and career personnel. There are eight full-time paid staff and more than 35 volunteers who work out of two fire stations.

The department operates on a VHF 153–155-MHz radio system. It is suitable to the local geography and terrain as its signals readily bend around obstacles. Each firefighter in the department carries a voice pager. Portable radios are located on each seat of the fire apparatus ensuring that each person staffing apparatus (e.g., fire engine) has a portable radio.

The area is a mixture of mountains, valleys, and flat terrain. In the mountains, communications are sometimes limited, and in some cases, blocked out entirely.

Both the shadowing of the mountains and limited numbers of repeaters often lead to these communication problems. Yet, the fire department reports that these pockets of limited radio communications are small enough to not cause serious problems. Most large ranges of dead spots are restricted to unpopulated areas.

Where communications are problematic, the department uses “human repeaters.” That is, each portable radio carried by a firefighter rebroadcasts or radiates the signal. Mobile repeaters are never used.

Another issue for the Boulder Rural Fire Department is interoperability. All of the surrounding counties use the 800 MHz radio systems. Therefore, firefighters from the Boulder Rural Fire Department are not capable of communicating directly with other firefighters working on an incident.

Brighton, CO

Brighton, Colorado is located approximately 20 miles northeast of Denver. The combination Greater Brighton Fire Protection District (GBFPD) has nine career and 60 volunteer uniformed personnel. The district is adjacent to Denver International Airport (DIA) and encompasses approximately 160 square miles of mostly rural Adams and Weld Counties, with a total population of 25,000.[18]

Recently, the GBFPD migrated from a 400 MHz radio system to an 800-MHz trunked system. However, due to the large number of volunteer personnel who rely on pagers, the District continues to simulcast its dispatch information on the 400-MHz band to activate those pagers. Nextel is gaining popularity in the region, particularly as more tower sites are added.

The GBFPD is currently working out some coverage issues with the 800 MHz system. Additional radio towers have reduced the number of “dead spots,” but communications into and out of schools in the district remain a problem.. For interior operations, the district generally uses simplex mode, rather than the trunked system, to enhance communications.

Interoperability in the region is also a struggle, as the high cost of 800MHz has deterred many city agencies and surrounding jurisdictions from adopting it. Several departments continue to use 400 MHz, while nearby Weld County remains on its 100 MHz system.

Finally, the emergency activation feature of the radios is not enabled; the district is in the process of developing procedures for emergency radio communications, e.g., Mayday situations.

Charlotte, NC

The City of Charlotte, N.C. is home to over 500,000 people who live within the 242 square miles of urban land area. It is surrounded by rolling hills.

According to the Charlotte Convention and Visitors Bureau, nearly 300 Fortune 500 companies have offices in Charlotte, as do 340 foreign firms.[19] The downtown includes high-rise buildings and other large structures (e.g., convention center, football stadium, etc.). There are no underground tunnels or subway systems.

The all-career Charlotte Fire Department provides services throughout the City of Charlotte and Mecklenburg County. It protects a population of over 600,000 and covers 270 square miles. There are 890 uniformed personnel in the department.

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[18] The City of Brighton has a resident population of 20,905. The remaining population served by the GBFPD is from Adams and Weld Counties.
[19] Charlotte Convention and Visitors Bureau (www.charlottecvb.org/visitor.cfm.)

For the past 14 years, the fire department has used an 800-MHz trunked system. The entire city government of over 11,000 people is on the network. The fire department operates on 28 channels, shared with the police department. Each firefighter has a portable radio.

Like many fire departments around the nation, Charlotte reports problems with transmitting signals outside of a high-rise building or basement structure. It is testing a mobile repeater to alleviate this problem. To date, it has had some success with the mobile repeater. For interior operations, the department uses simplex mode – radio to radio – to communicate to, from, and within a building or structure. The mobile repeater has added robustness to the core of the structure, allowing better communications among firefighters on the simplex mode. Without the mobile repeater, the portable radios do not have the strength to reach the stationary repeaters.

Interoperability between outlying counties is another problem. As a solution, the city has provided neighboring jurisdictions with Charlotte radios.

The Charlotte Fire Department does not have overcapacity troubles. The department has standard operating procedures designed to shut down various parts of the system (i.e., private line on the radio, interconnect system, etc.) to ensure no overcapacity.

Lastly, a proposal to improve fire communications in high-rise buildings by requiring a built-in communications infrastructure was defeated.

Chicago, IL

The Chicago Fire Department is one of the premier firefighting organizations in the world. It is one of the largest in the United States with nearly 4,000 uniformed personnel, protecting 3 million citizens over nearly 240 square miles. In addition, the department provides fire suppression services to one of the world’s busiest airports – O’Hare International.

Communications are provided to the Chicago Fire Department by a separate department, the Office of Emergency Communications (OEC), otherwise known as the “9-1-1 Center.”

Chicago uses a conventional VHF system with two dispatch channels, one reaches citywide. Three simplex channels are used for fire operations and one command channel. Company officers all carry portable radios, and the department is in the process of issuing more – one radio for every two persons.

As a whole, the Chicago Fire Department reports that it experiences few communication problems because it deploys a multi-simulcast radio system and 10 transmitter sites (per channel). The system has diversity: up to 32 receivers are within any 12 square miles area. Unlike many urban departments, Chicago has no plans to change its communication system to 800 MHz. Because of number of receivers around the city, communications with dispatch via portable radios functions well.

One challenge the department has is the inability of the fire department to talk directly with law enforcement and emergency medical services (EMS), which they operate on a different radio system (UHF). EMS and the fire department respond jointly on most incidents, so the fire department does have some access to the UHF system. A more permanent solution to this problem is being worked on, which will use technology to patch the systems together. The department deploys a command vehicle to every major incident. These vehicles have a suite of radios installed for communications by the incident commander with the various departments (e.g., fire, EMS, police, etc.).

Considering the large number of high-rise buildings, the Chicago Fire Department is advocating built-in infrastructure within the structures. Currently, most in -building coverage is achieved with portable, simplex radios. There are occasional “dead spots” within some high-rise structures, basements, etc. These are considered “incident specific problems,” not system-wide.

Subway communications are accomplished on a UHF frequency (same as law enforcement and EMS). As a result, the fire department cannot use its radios to communicate within the subways with the necessary authorities. In such instances, department personnel use EMS radios.

Clark County, NV

Clark County is located in southern Nevada. On a regional level it has a population of more than 1.5 million residents spanning an area of 8,000 square miles. Most of the population lives within the Las Vegas valley. Some of its incorporated areas are Las Vegas, North Las Vegas, and Henderson. The county includes both urban and rural areas.

The Southern Nevada Area Communications Council, also known as SNACC, manages most fire department communications, including those for the City’s of Las Vegas, North Las Vegas, and Henderson and unincorporated Clark County. SNACC was created as a Joint Powers Authority by each of these jurisdictions. Each municipality buys into the system and pays annual operating costs. The communications network managed by SNACC covers approximately 4,000 square miles.

Each department operates on an 800-MHz trunked radio system. There are a total of 20 channels, with mobile radios are located in each piece of fire apparatus. Portable radios are located on each seat of the fire apparatus ensuring staffing personnel a means of communication.

Despite its desert environment, Clark County has high mountains that make communications difficult. The tallest mountain is 12,000 feet. There are some others that reach heights of 9,000 feet.

Casinos and other high-rise buildings present challenges. There are many in-building coverage issues. The size and construction of the buildings can shield RF signals, and, the Casinos are often very noisy (a combination of lots of people and slot machines), making it difficult for firefighters to hear radio communications. Interference from the Casino’s own communication systems can disturb the fire department radio system. Lastly, each casino has at least one below ground level, in the basement.

To manage the communication problems, SNACC and the local fire department sometimes post a firefighter in the security office of a casino to use both the fire department radio communications and the built-in communications system of the casino.

Many of the casinos and other large buildings are wired with radio accessories, such bi-directional amplifiers. SNACC and the participating fire departments recently purchased mobile repeaters. They have not been tested.

Like many other areas around the country, Clark County is experiencing interference with wireless communications towers, most notably Nextel. The county is awaiting final approval between the Federal Communication Commission and Nextel on a plan that addresses interference to public safety communications in the 800-MHz band. This plan is known as the Joint Commentors' Consensus Plan.

The goal is to eliminate interference to public safety communications on the 800-MHz band; to cause minimum disruption to existing services; and to provide sufficient spectrum for public safety users. It divides the 800-MHz band into two separate blocks of channels. The first is intended for public safety. The other block of channels would be used for Nextel and its wireless communications.

Dallas, TX

Dallas is one of the largest cities in the Southwest, and the seventh largest in the U.S. It is a major business and financial center, and also one of the top convention cities in the United States.[20] It has numerous tall buildings, (with 25 buildings greater than 30 stories). The elevation of the city is between 450-750 feet, and there are many below ground structures, such as basements, sub-basements, and parking garages.

Dallas Fire-Rescue (DFR) covers 378 square miles and a resident population of approximately 1.2 million. The department operates out of 55 fire stations, and currently has nearly 1,700 uniformed firefighters.

DFR operates on a 400MHz UHF radio system. Each firefighter has a portable radio. There are four simplex channels for operations. The simplex channels are limited by distance. Interior fire operations sometimes create a communications problem. To communicate outside a structure, DFR sometimes has to relay the message via a runner through an egress stairwell. .

Police and fire can communicate with each other, through a "patch system." Dispatch will patch police and fire together, and they can talk directly to one another.

[20] The Dallas Convention and Visitors Bureau (www.dallascvb.com/visotrs/today.php.)

The department has done some investigative research and considered upgrading to an 800 MHz radio system. However, the upgrade has not been pursued due to a lack of funding, and also because the department concluded that the 800 MHz radio system did not meet the needs of the city for 95 percent coverage.

Detroit, MI

Detroit has a residential population of over 950,000 across 139 square miles. The Detroit Fire Department (DFD) protects the city's population with nearly 1,300 career firefighters.

DFD uses a 400 MHz radio system, which has been in place for nearly 30 years. The Department is responsible for fire as well as EMS dispatching. Currently, DFD has one repeated channel for dispatch, four fire operations channels, and one channel for EMS. Some tactical fire operations channels are also repeated.

Commanding officers for each fire company have portable radios. Personnel at or above the rank of Battalion Chief are also issued cell phones and pagers.

Most communications problems are concentrated in the downtown area due to the high number of high-rise buildings, such as office buildings, apartment buildings, and other large structures. The Department has added repeaters to buildings and other areas of the City to alleviate these problems. Nonetheless, they still occur. There was an incident reported in which a firefighter used his cell phone to contact the command post outside.

Firefighters also report equipment problems, notably that the portable radios are not waterproof. Also, they report that down tower sites and broken repeaters have hampered communications.

The department is upgrading to an 800 MHz system at the end of 2003 to be able to communicate with all city departments (such as police, etc.). Some firefighters are opposed to the upgrade, as they fear that the new radio system will not work as well in sub-basements and other structures.

Everett, WA

The Everett, Washington Fire Department (EFD) is a full-time, career fire department that protects roughly 90,000 residents. Although the City boundaries encompass 41 square miles, only 28 square miles are land, the other 14 are water. Everett is home to the USS Abraham Lincoln Aircraft Carrier Group, as well as other marine vessels. Everett's coverage area includes a Boeing aircraft assembly plant, which is the largest enclosed structure in the world. Numerous warehouses and high-rise buildings complement the array of single-family homes throughout the city.

The terrain includes hills throughout the City limits, with the northwest part of the city, along the waterfront, sitting considerably below the rest of the city. Everett is 80 miles south of the Canadian border.

EFD has used VHF radios with fairly good success. Problems with building penetration have been rare. With a portable radio, personnel can talk throughout half of the city. As a result of Canada reclaiming some of the VHF frequencies and essentially narrowing the available bandwidth, the EFD is implementing a new 800 MHz system in summer 2003, which will provide 95 percent coverage throughout the city limits.

The communications problems encountered the current system are related to limited tactical channels and operation in a firefighting environment. Specifically, the EFD only has access to its dispatch channel and one tactical channel. When simultaneous incidents require a tactical channel, the incidents will need to share the one tactical channel or one will have the tactical channel while the second uses the dispatch channel for its operations.

The EFD has experienced numerous problems due to use of full personal protective equipment (PPE) and SCBA. Members of the EFD have experienced difficulty operating the portable radio, especially the channel selector and volume control while wearing the bulky firefighting gloves that limit dexterity. Radio transmissions have been difficult to understand from the interior of a firefighting operation because voice distortion is created through the mask. Also mentioned by EFD staff is that voices are often difficult to understand because the interior firefighter transmitting is often out of breath. And lastly, since all firefighters have a portable radio when assigned to fire department apparatus, they do not cover their radio microphones or turn them off completely, a situation not recommended from both a safety and operational perspective.

The EFD reports success during radio transmission in new buildings with leaky coaxial cables. The EFD is working diligently to have some older building retrofitted with this technology to further enhance the quality of radio transmissions.

Fairfax County, VA

Fairfax County, Virginia is located just outside Washington, D.C. The county encompasses nearly 400 square miles with a resident population of approximately 970,000. The Fire and Rescue Department has 1,166 uniformed staff who responded to 89,246 calls for service in FY2002.

The county includes various structures, ranging from standard residential and commercial buildings to secure government installations (e.g., the Central Intelligence Agency's Headquarters).

The fire department currently uses an 800-MHz trunked digital system for communications with 20 available frequencies. Communications are simulcast on the department's "old" 460 MHz channel as well. Dispatch and operations are separated; units are dispatched on one channel, while day-to-day operations are handled on another. Fairfax County is acquiring 20 additional analog channels, which will provide a back-up system should the digital system fail.

For working incidents, operations and command are assigned to additional channels to avoid impinging on tactical communications. The incident commander monitors the command and incident channels, as well as a talk-around channel for structures with communications problems. Fairfax uses two available talk-around channels, which are not repeated. In the event of communications problems during an incident, the incident commander can order all units on the incident to switch to the talk-around channel.

Recently, the department purchased the Incident Commander Radio Interface (discussed in more detail in Chapter III) for use by the communications officer and to interface the talk around channels with operational channels. The department is developing Standard Operating Procedures for using the device.

The department reports that there are a variety of dead spots in the county, particularly in and around a large regional mall as well as the local trauma center. To address these issues, the county is constructing three additional tower sites, for a total of 11 throughout the county. Also, a recent ordinance requires new buildings to maintain radio coverage throughout the structure. This has been accomplished in the county's new jail, which has a combination of a bi-directional amplifier and leaky coaxial cable in the ceilings (see Chapter III for more details).

Since transitioning to an 800 MHz system, Fairfax has had one failure, where the system entered "Failsoft" (a condition where specific channels are maintained, while the majority are offline). As a result, the dispatch center is preparing contingency plans to address such incidents in the future. More on such plans can be found in Chapter III

Fairfax County's public safety is experiencing system coverage degradation from Nextel (interference). The Nextel system, also operating on the 800-MHz band, appears to be incompatible with the pre-existing systems in the 800-MHz band. One proposed solution by the Department of Information Technology is to move Nextel out of the 800-MHz band. The county is opposed to reorganizing or restructuring its public safety radio system.

The fire department, has issued some officers Nextel cellular phones. The department is in the process of purchasing these phones for all front-line suppression and EMS apparatus (medic units are already equipped with a conventional cellular phone for hospital communications).

Gettysburg, OH

The Gettysburg Rural Fire Department is a private, all-volunteer department. Located in Darke County, the department protects a population of approximately 3,700 over a 60 square mile area. The department operates out of a single fire station. Total call volume is about 190 calls per year – 110 EMS calls and 80 fire calls.

Mostly rural, and residential with some commercial structures, Gettysburg's commercial structures are privately owned farmhouses. The tallest structure is about two stories. The geography and terrain of the area is mostly flat, with some hills.

The department operates on a UHF radio system (154-MHz) that includes four tactical operations channel and one dedicated dispatch center.

The biggest challenge for fire department radio communications is interference. In Gettysburg, firefighters often encounter radio interference from the neighboring Miami County. Miami County, located to the east of Darke County, sits at a higher elevation and has higher towers. Although Miami County uses the 800 MHz radio system, it dispatches off of UHF. During its dispatches, it virtually blocks out communications to the Gettysburg Rural Fire Department.

One solution is increased system design and infrastructure for Darke County. However, due to a shortage of money, the county cannot presently afford to add more system infrastructure.

Los Angeles, CA

The Los Angeles Fire Department (LAFD) protects approximately 3.7 million people who live in the second largest city in the United States. The department has over 3,200 uniformed personnel, operating out of 103 fire stations, covering a land area over 470 square miles.

The LAFD uses a conventional 800 MHz system, which has been in place for the past decade. Every firefighter is issued a portable radio while on duty. There are 18 channels; three of which are dispatch channels broken down by Metro and Valley area. The city is divided into three regions, and each has a channel. There is also one command channel for the chiefs.

The location of a Nextel tower is one challenge for the department. The Nextel operates on the same frequency and can cause radio interference.

It is hard to maintain radio coverage for a city of this size and diverse topography, Hills and mountains present challenges. These general challenges do not regularly occur... Still, the LAFD has worked carefully on the strategic placement of towers and repeaters to address coverage concerns. And, in those are where dead spots are more frequent, the city has back-up repeater sites. .

A common problem in many cities, communications in subways and tunnels present few challenges for the LAFD because the subways and tunnels are wired with underground cables, which carry a signal for four or five of the fire department channels.

For major incidents, the LAFD reports no operational problems with the communication system per se; problems the department experiences are more of logistical issues. The system can handle the capacity, but since multiple channels may be used at the same time, firefighters are not always on the correct channel.

Interoperability is another difficulty for the fire department. Because the police and public works departments operate on a different radio system (500 MHz UHF band), the fire department cannot communicate directly with these departments.

Milwaukee, WI

The Milwaukee Fire Department protects a population of about 600,000 spread over 96 square miles. There are 1,100 sworn personnel in the department.

Currently, the Milwaukee Fire Department (MFD) uses a 400 MHz system with eight channels. Two channels are dedicated to dispatch; one is the main dispatch channel and the second is for the officers on the fireground to call dispatch. Five other channels are for fireground only. There is no interoperability with other city agencies.

Overall, the communications system works about 98 percent of the time. The technology and equipment were not reported as issues.

There are some spots (e.g., buildings and basement levels) where equipment does not work. For high-rise structure fires (anything over five stories), it is the department's policy to put the command center in the lobby of the building (if it is safe to do so). Typically, there is good communication within the building. If they experience problems, they will use a runner.

The single biggest problem the department has with communications is human error: firefighters do no know what channel they are on and do not communicate frequently with incident commander. The department considers this problem to be an issue of accountability and not a training problem.

Phoenix, AZ

The Phoenix Fire Department protects a population of nearly 1.4 million across 500 square miles. It has over 1,366 sworn personnel that operate from 47 fire stations. In 2002, the fire department responded to 133,519 calls – 104,635 EMS calls and 28,884 fire and non-EMS calls.

Currently, the fire department uses a conventional direct radio communication system in VHF. The primary infrastructure – two tower sites above the North Mountain and South Mountain and diversity receivers – does not use repeaters. The diversity receiver operates like a small radio tower and receives the emitted radio signal on several antennas. The department operates 24 VHF channels and there are 36 diversity receivers per channel.

The department has had much success with this system. However, there are some challenges. High-rise buildings, basements, and any other structure with dense concrete may cause communication problems. With this system, the two major difficulties are fade and feedback. Where people are clustered together and one person transmits, there is lots of feedback. Fade is more related to the distance between one radio transmitting a signal and the other receiving it. The sound is usually muffled and difficult to understand.

Like many departments, Phoenix has problems using portable radios in a hostile environment, a working fire incident with zero visibility and wearing full personal protective equipment. The Phoenix Fire Department had a fire fatality a few years ago. The Department determined three factors the department needs to ensure firefighter safety – airway management, firefighter rescue techniques, and radio communications. The firefighter did issue a “mayday,” and was heard over the radios. The fire department could not locate and rescue the firefighter before his death.

Dead spots are, for the most part, not a problem for the fire departments. The diversity receivers are strategically located throughout the City. There are a lot of them. Each receiver has the ability to receive a radio signal from within a 2-mile radius.

The City of Phoenix is incorporating an 800 MHz digital trunked radio communications study. This is not the fire departments preference, but rather a recommendation that was made by a consultant for the police department. In addition, there is a big cost savings for the City to operate on the 800 MHz system. The City only has to operate and support one radio system. Also, there is less combined infrastructure. The system is being split by Phoenix and Mesa, Arizona.

The conventional VHF radio system with diversity receivers has been successful. The fire department reports effective use on the fireground. While each channel on the 800-MHz trunked system is repeated, it must reach a tower to communicate. That is not the case for the current system. Even if simplex or talk-around channels are built in to the system (part conventional), firefighters wearing full PPE still have difficulty changing channels in a dark, hostile environment.

The department reports that transitioning to the new communications system puts firefighters lives at greater risk. The Department must train each firefighter on the new system, whole changing current behaviors and adapting new ones for the current system. Training is to begin soon on the new system, before it is implemented in 2005.

Pittsburgh, PA

Pittsburgh, a mountainous city, covers 57 square miles. The Pittsburgh Fire Department serves a population of 360,000. The largest concentration of commercial activity is in the downtown area where there are numerous high-rise buildings.

The fire department is part of a centralized UHF communications system for all city services—emergency, police, fire, etc, with a single, centralized dispatch. However, a single channel is dedicated to fire dispatch, another to fire ground communications, and then additional channels are available on demand, whenever necessary. This flexibility to use more or less channels has proved helpful for the department in the past.

Large and high-rise structures, below grade structural areas, and tunnels areas pose the greatest communications problems for the Pittsburgh fire department. If the firefighter inside cannot communicate to the outside, the department bypasses the repeaters and goes to two-way radio talk around system for communications. The department uses these radios in other situations as well, whenever the mountains interfere with reception on the larger system. Pittsburgh's talk around radios have a ½-mile communications radius. Cell phones and pagers are used strictly for administrative purposes, although most of the firefighters carry one or the other.

The communications system for the City of Pittsburgh seems to work well. Department staff have noted that an improvement it would be "portable radios with built-in repeaters" for the fireground.

Portland, OR

Portland has a population of over 525,000 within city limits, and 1.8 million living within the metropolitan area. The city is approximately 130 square miles, situated 50 miles inland on the Columbia River midway between the Coast to the west and Cascade Mountain range to the east. The Columbia River is quite wide and Portland has one of the West Coast's largest ports. The city is surrounded by the West Hills. Also in the vicinity of the City are Mount Hood and Mount Saint Helens, two volcanoes over 10,000 feet.

Portland has a citywide consolidated communications system on an 800 MHz Motorola "Smart Zone" system. Set up in 1994, the system has had several software upgrades.

There are 13-talk group channel and 1 administrative channel for the fire department. It is estimated that the system is running at 40 percent capacity. Each company has a mobile data terminal and three portable radios. The officer, the driver, and one two-person team have a radio (apparatus are staffed with four personnel). The city has four primary simulcast transmitter sites and 11 small repeaters. A fifth transmitter site has been planned, but has not been put into operation.

The terrain surrounding Portland creates communication problems in shadowing and dead spots. To curb such difficulties within the central area, the city placed a large antenna above the West Hills. Coverage is still a problem in high-rise buildings, basements and sub-basements, and the light rail system underground tunnels. The tunnels have built-in antenna system, which alleviates most of the communication problems.

In addition, the harbor provides significant communication problems. The fire department has many shipboard incidents and while the port also has antennas and other communication support equipment, communications are a problem below deck.

To resolve some of its communication challenges, the department uses its simplex talk around channels in areas where communications are challenging. The department has created specific SOPs for such incidents, and trains on them as well. The Department is also in the process of acquiring mobile repeaters for chief vehicles.

The city also experiences problems with the Nextel cellular phone system. As with other departments, the Nextel system, also operating on the 800-MHz band, is incompatible with the pre-existing systems in the 800-MHz band. To prevent major interference with fire department communications, Nextel and the fire department swapped frequencies to resolve the problem. The fire department gave up a channel on the end of their radio band for Nextel's channel in the middle of the city's band.

San Antonio, TX

The City of San Antonio is the ninth largest city in the United States and third largest in the State of Texas. It has a population of over 1.1 million and a land area of more than 400 square miles. The San Antonio Fire Department serves the City with more than 1,000 uniformed firefighters operating out of 48 fire stations.

San Antonio is large, so, the fire department often provides fire protection and response to its many high-rise buildings (some 30-40 stories) and other large structures such as the Alamo Dome, SBC Center, a Convention Center, Coliseum, etc. There are no underground tunnels or transportation systems.

The San Antonio Fire Department uses a Motorola Simulcast System (UHF), with eight channels: one dedicated for dispatch, two for EMS, and the remainder for tactical fire operations. Each channel is repeated.

The city is upgrading to an 800-MHz Trunked system by the end of this year. It is upgrading because the old system is antiquated. Some parts are no longer made for the radios and other equipment is outdated. The radios are also less resistant when exposed to hazardous conditions, such as water.

There are no inadequate system capacity issues in the department. . However, there are some "dead spots" in the city, scattered about. There are also dead spots in some of the unincorporated type areas outside of the City (where the SAFD provides service). It is believed that the dead spots are generally caused by a lack of infrastructure – not enough repeaters, transmitters, etc. The department believes that adding new infrastructure (as part of the new 800 MHz upgrade) and strategically placing towers and repeaters, will resolve some of these issues.

Interoperability is important communication problem for the department. The fire department cannot communicate with other city agencies or neighboring jurisdictions. In order to communicate with other city department, the dispatch center will "patch" the various departments together.

The 800 MHz system has already been tested in the city, with 95 percent coverage. The All city agencies will be on the 800 MHz system, possibly the county's sheriff's office too. Other jurisdictions, if they choose, may also be on the city's system (by leasing space from the city). The new system will have a lot of built-in infrastructure – 11 Tower sites. The city will own the entire infrastructure. Each firefighter will be issued a portable radio.

San Diego, CA

The San Diego Fire-Rescue Department (SFRD) consists of 1,100 uniformed personnel who operate out of 44 stations and serves a population of 1.3 million people across 330 square miles. The Department's response area includes high-rise buildings, warehouses and other "typical" city hazards as well as miles of beach and shoreline.

The department uses a Motorola 800 MHz system, which has been in place for 11 years. The operations units also carry VHF portables because neighboring departments (to which SFRD provides mutual aid) use this system. Dispatch and operations channels are separate; channels are assigned by geography. Each battalion (7 total) operates on its own channel. There is also one channel for all medical calls and one channel for all traffic incidents. Each channel has repeaters that are located throughout the City, either on mountaintops, high-rise buildings, etc.

Until recently, SFRD used a VHF communications system. Unfortunately, the city was unsuccessful in eliminating VHF interference from Mexico and has since migrated to the 800 MHz system.

The 800 MHz system works, but the major challenge for the city is to train 1,000 firefighters and 2,000 police officers to use it. The system is more complex than the one it replaces, and there are some in the department who are very good with the radios while others are not.

To combat dead spots in structures, the department will use firefighters as mobile repeaters. In other words, a firefighter will stand at a stairwell support (within line of sight), another firefighter will be below him, etc. and the message is repeated to the outside.

For the Super Bowl, the department used a Mobile C.O.W. (Cellular on wheels), which acts as a mobile antenna to allow communications to be repeated outside a building. This technology is also used for the San Diego Convention Center. The Mobile C.O.W. is run through an underground tunnel, beneath the convention center.

Cruise ship fires also pose a challenge – ships have a radio on each deck at each door. The department typically needs to set up firefighters as mobile repeaters to facilitate communications.

The department also uses cell phones and issues personnel alphanumeric pages. Senior staff is issued Blackberry wireless devices.

San Francisco, CA

San Francisco has a population of more than 775,00 spread over a small area, 49 square miles. The San Francisco Fire Department (SFFD) has more than 1,700 uniformed personnel operating out of 42 stations.

The city operates an 800 MHz radio system and has for the past eight years. Prior to that, the city was using an older Motorola 400 MHz system. The newer system allows the department to have more working channels and interoperability. There are 16 channels; three controlled for dispatch. Each battalion has an assigned channel. There are 10 battalions.

Despite the upgrade, the radio system is still limited inside high-rises. Dead spots still exist, but most have been eliminated.

The department has added more towers and repeaters. It is currently upgrading the system with portable repeaters. The city is moving repeaters to higher areas of the city, to prevent interference from other high-rise buildings.

BART, San Francisco's underground public transportation system (subway), does pose some communication problems for the SFFD. Radios for BART are issued to fire stations located near subway stations. These radios are also carried by some Battalion Chiefs.

There is no interference from the shipping channels.

Schaumburg, IL

The Schaumburg Fire Department (SFD) , a full-time career fire department, is located approximately 30 miles northwest of Chicago. Schaumburg has a resident population of approximately 75,000 people and encompasses roughly 20 square miles of mostly flat terrain. The SFD response district includes single-family residences, multi-story residential structures, including hotels, and high-rise commercial office buildings.

The SFD has used 800 MHz technologies since 1988. Its initial 800 MHz system had one antenna site for the entire Village. A new system, which went on-line in April 2003, uses four antenna sites. Under its old system, the SFD experienced numerous dead spots throughout the Village where firefighters could not receive nor transmit radio traffic. Personnel of the SFD also had difficulty transmitting out of and into structures that used Lexan glass as windows or buildings that used significant amounts of concrete in construction.

Most of the radio/communication problems the SFD experienced were in high-rise structures, which typically employ large amounts of concrete and Lexan glass during construction. The only reliable way the SFD could transmit out of high-rise structures was if the firefighter stood at the window. The SFD has experienced very few problems while operating at single-family residential structure fires.

The SFD, which shares the 800 MHz system with Law Enforcement and Public Works, frequently experienced busy signals under the old system that utilized only three trunks. In its research for expanding its network of trunks, the SFD found from the FCC that few trunks are available; the SFD was able to purchase a trunk from a bus company in New Jersey that went out of business.

The new radio system and its new antenna sites have dramatically improved communications during structural firefighting events for the SFD. New building codes required signal boosters during construction for certain types of buildings. This has also helped improve communications for the SFD.

Like many departments, the SFD struggles with the portable radio and the ease of using it in a zero-visibility environment, while wearing bulky fire department gloves. The only solutions that the SFD has come up with as a precautionary measure, as have other localities, is to program the extremes of the channel selector on the portable radio (selector turned all the way left or right) to the same, recognizable channel (usually dispatch) regardless of zone selection. If the firefighters operating in a zero-visibility environment accidentally change the radio from the tactical operations channel and are not able to find the appropriate channel, they can turn the selector all the way in either direction to ensure that they will be able to talk to a dispatcher in the event they need help.

The SFD has enhanced radio interface and operability with its mutual aid neighbors by utilizing transponders on the apparatus and command vehicles that can convert VHF radio to 800 MHz and vice versa. This way, the SFD can continue to operate with only one radio system.

Springfield, NJ

Springfield, New Jersey is located about 23 miles southwest of New York City. The township encompasses 5.06 square miles of mostly flat terrain, which contains a combination of residential, commercial, and industrial structures. Springfield has a resident population of 14,250 and a daytime population of 30,000.

The Springfield Fire Department (SFD) is a combination department, comprised of approximately 33 career and volunteer firefighters and officers. The SFD currently uses a high band radio system, at approximately 470 MHz. The Chief and Deputy Chief (as well as other senior Township officials) are issued also Nextel cellular phones to facilitate communication between these officials.

Unlike many departments nationwide, the township reported that the SFD does not typically experience difficulties transmitting in and out of structures or from floor to floor. Instead, the department contends with radio interference from two neighboring jurisdictions that operate on similar frequencies. In both cases, the jurisdictions are at a higher elevation than Springfield and have higher radio towers. Depending on the weather and time of day, transmission from these departments “step on” SFD operations, making it difficult for units to transmit or receive messages from dispatch.

To alleviate issues with neighboring jurisdictions, discussions are underway to study the feasibility of trunking the current radio system because there are not enough frequencies available for the SFD to completely modify their radio system (e.g., transition to 800 or 900 MHz).

Wichita, KS

The Wichita Fire Department (WFD) serves over 340,000 residents of Wichita. The city, located in Sedgwick County, has a diverse economy that includes agricultural services, aviation, and oil and gas production. The City serves a large hinterland in central Kansas. The Fire Department covers over 136 square miles of the City. The Department provides a full range of fire, rescue, hazardous materials, and other services.

The Wichita Fire Department operates on an 800-MHz trunked system. This system has been operating for approximately 10 years. The fire department has one dispatch channel, one operations channel, seven tactical channels, one channel for Administration, and one command channel (for multi-agency use). Each company has a portable radio (company officers).

Prior to the 800 MHz system, the city had an old 2-channel system. Even with additional repeaters and other modifications, problems stemmed from a lack of channels.

All of the public safety departments within the City are connected to the 800 MHz system.

Interacting with surrounding jurisdictions, also using an 800 MHz system, is problem for the WFD. Some of the surrounding jurisdictions are not tied into the Wichita system.

The WFD also experiences problems communicating in elevators, large buildings, basements and sub-basements, and malls. There is often difficulty in transmitting a signal. The lower level of the mall has difficulty transmitting and receiving. To reduce the magnitude of the problem, firefighters must use the “talk around” channel, or simplex mode (radio to radio).

The department has added repeaters in the past, with some success. The department knows which buildings have problems and do their best to work around them. There are relative few “dead spots” around the city.

The WFD would like to try mobile vehicles, but does not have the financing. The city does not have any built-in radio ordinances for buildings.

GLOSSARY OF TERMS AND ABBREVIATIONS

Terms

Attenuation - The decrease in intensity of a signal, beam, or wave as a result of absorption of energy and of scattering out of the path to the detector, but not including the reduction due to geometric spreading.

Diffraction - The deviation of an electromagnetic wavefront from the path predicted by geometric optics when the wavefront interacts with, *i.e.*, is restricted by, a physical object such as an opening (aperture) or an edge.

Duplex – *A communications mode with the ability to transmit and receive radio traffic simultaneously through two different frequencies, one to transmit and one to receive.*

Multipath – The propagation phenomena that results in radio signals' reaching the antenna by two or more paths. Causes of multipath include atmospheric ducting, ionospheric reflection and refraction, and refraction from terrestrial objects such as mountains or buildings.

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

Project MESA – Project MESA is an international partnership producing globally applicable technical specifications for digital mobile broadband technology, aimed initially at the sectors of public safety and disaster response.

Rake Technique - A receiver technique that uses several baseband correlators to individually process several signal multipath components. The correlator outputs are combined to achieve improved communications reliability and performance.

Reflection - The abrupt change in direction of a wavefront at an interface between two dissimilar media so that the wavefront returns into the medium from which it originated.

Refraction - Retardation, and—in the general case—redirection, of a wavefront passing through (a) a boundary between two dissimilar media or (b) a medium having a refractive index that is a continuous function of position, *e.g.,* a graded-index optical fiber.

Repeater - An analog device that amplifies an input signal regardless of its nature, *i.e.*, analog or digital. A digital device that amplifies, reshapes, retimes, or performs a combination of any of these functions on a digital input signal for retransmission.

Scattering - Of a wave propagating in a material medium, a phenomenon in which the direction, frequency, or polarization of the wave is changed when the wave encounters discontinuities in the medium, or interacts with the material at the atomic or molecular level.

Simplex – A communications mode with the ability to transmit or receive in one direction at a time. Simultaneous transmission cannot occur.

Trunking – In radio in communications, it is a system that may include a single user of different workgroups, which uses a group of radio frequencies (a trunk). The system is dynamically controlled by a computer, which directs a transmission to an available channel or frequency.

Wavefront - The surface defined by the locus of points that have the same phase, *i.e.*, have the same path length from the source. 1. The wavefront is perpendicular to the ray that represents an electromagnetic wave. 2. The plane in which the electric and magnetic field vectors lie is tangential to the wavefront at every point. 3. The vector that represents the wavefront indicates the direction of propagation.

Abbreviations and Acronyms

3G	third generation
ac	alternating current
AGC	automatic gain control
AM	amplitude modulation
AMPS	advanced mobile phone system (cellular system)
AOA	angle of arrival
ARRL	American Radio Relay League
ATM	asynchronous transfer mode
AWGN	additive white Gaussian noise
BDA	bi-directional amplifier
BFRL	Building and Fire Research Laboratory
BPL	broadband power line
bps	bits per second
CDMA	code division multiple access
CFP	contention-free period
cm	centimeter
COW	Cellular on Wheels
CP	contention period
CSMA	carrier sense multiple access
DARPA	Defense Advanced Research Projects Agency
dB	decibel
dc	direct current
DCF	distributed coordination function
DES	Data Encryption Standard
DSL	digital subscriber line
DSP	digital signal processor
DTIC	Defense Technical Information Center
EDCF	enhanced distributed coordination function
EHF	extremely high frequency
ELF	extremely low frequency
EMS	emergency medical service
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FDNY	Fire Department of New York
FEC	forward error correction
FEMA	Federal Emergency Management Agency

FM	frequency modulation
FSK	frequency shift keying
GHz	gigahertz
GIS	Geographic Information System
GPS	Global Positioning System
GSM	global system for mobile communication (cellular phone technology)
HC	hybrid coordinator
HCF	hybrid coordination function
HDTV	high-definition television
HF	high frequency
HVAC	heating, ventilation, and air conditioning
Hz	hertz
IAL	Intel Architecture Laboratories
ICP	incident command post
IETF	Internet Engineering Task Force
IF	intermediate frequency
IP	Internet protocol
ISL	Information Systems Laboratory
ISM	industrial, scientific, medical
kHz	kilohertz
km	kilometer
LAN	local area network
LCD	liquid crystal display
LF	low frequency
LOS	line of sight
LV	low voltage
M	mega
m	meter; milli
MAC	medium access control
MANet	mobile area network
MEA	mesh-enabled architecture
MHz	megahertz
MIMO	multiple input, multiple output
MRS	Mine Radio Systems Inc.
MSSI	Multi Spectral Solutions, Inc.
MV	medium voltage
mW	milliwatt
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NLM	National Library of Medicine
NLOS	non-line of sight
NOI	notice of inquiry
NPRM	notice of proposed rule making

NTIA	National Telecommunications and Information Administration
OFDM	orthogonal frequency division multiplexing
OOK	on/off keying
PAM	pulse amplitude modulated
PAN	personal area network
PAS	personal accountability system
PASS	Personal Alarm Safety System
PCF	point coordination function
PCS	personal communications system
PED	personal emergency device
PLC	power line communication
PLL	phase-lock loop
PN	pseudo noise
PPE	personal protective gear
PPM	pulse position modulation
PRF	pulse repetition frequency
PSWAC	Public Safety Wireless Advisory Committee
QDMA	quadrature division multiple access
QoS	quality of service
RF	radio frequency
SBIR	small business innovation research
SCBA	self-contained breathing apparatus
SDTV	standard-definition television
SHF	super high frequency
SNR	signal-to-noise ratio
TDMA	time division multiple access
TDOA	time difference of arrival
TTCP	The Technical Cooperation Program]
TTE	through-the-earth
UHF	ultra high frequency
USFA	U.S. Fire Administration
UWB	ultra wideband
VCO	voltage-controlled oscillator
VHF	very high frequency
VLF	very low frequency
WAP	Wireless Application Protocol
WLAN	wireless local area network
WPAN	wireless personal area network
WPI	Worcester Polytechnic Institute

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15 17 18 19 20 21 22 23 33 41 104 105 115 116 127 128 129 130 173 174 175 177 179 180 186 187 198 204 205 207 211 213 262 287 288 291

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Ultra Wideband

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