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

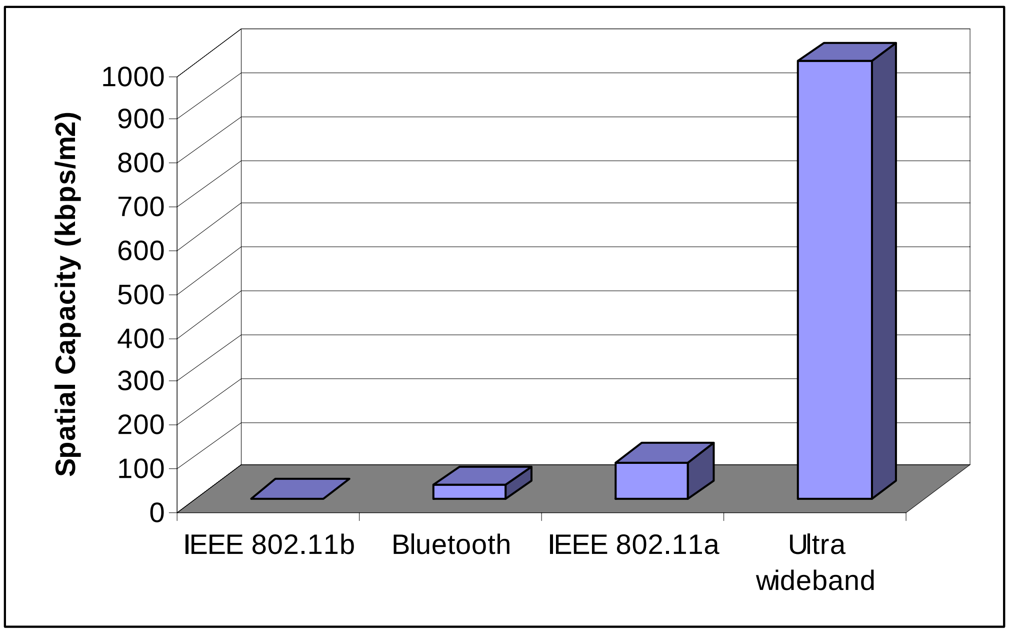
Several technologies are competing for the high-data-rate, short-range market for which UWB is suited. These technologies include wireless LAN (IEEE 802.11a, IEEE 802.11b) and Bluetooth (Table 8). Figure 7 shows that none of these competing technologies provide nearly as much spatial capacity as UWB. [**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
	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
	Man-portable and vehicular-mounted antenna development should be supported particularly as it addresses firefighting requirements.	70
	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
	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
	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