Research on Personal Area Network (PAN) Interference and Compatibility Issues for Public Safety Personal Protective Equipment

MERCER ENGINEERING RESEARCH CENTER
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EXECUTIVE SUMMARY

The purpose of this project was to research, collect and analyze data pertaining to the impact that the growing number of wireless devices has upon the first responder and the spectrum of electronic safety equipment (ESE) devices in their personal area network (PAN). A PAN refers to any network created by any electronic or communications device in a person's proximity. Local first responder agencies typically select their wireless devices and ESE based on cost and availability. This approach does not often account for the possibility of incompatibility and the potential for harmful interference with other systems and the users themselves.

To investigate the effects of multiple wireless devices on human performance, Mercer Engineering Research Center (MERC), in collaboration with Mercer University, Guardian Centers, and High Velocity Human Factors, executed a detailed research plan based on DHS defined objectives. That plan included the selection of radio frequency (RF) and human factors instrumentation equipment, a detailed study of the current and future state of the public safety RF spectrum, planning and participation in multiple medium/large first responder exercises, and the analysis of the collected data. The objectives of the research were to observe in a naturalistic setting, rather than in a laboratory, the kinds of communication losses experienced by first responders during emergency responses and determine the causes and effects of communication losses.

State of Public Safety RF Spectrum

In recent years, public safety wireless technology has received increased attention. This is primarily due to better awareness of the need for reliable communications for the first responders in the aftermath of events such as the September 11, 2001 terrorist attack, Hurricane Katrina and the Boston Marathon bombing.

The critical issues facing public safety radio communications are the need to enhance interoperability, to offer adequate network capacity and capabilities, to provide broadband connectivity, and to cope with traffic congestion and RF interference in the event of an emergency situation. Most of these issues should be addressed by the broadband LTE-based FirstNet system, currently under development.

Exercises and Events

Specific events were chosen for relevance based on the number and types of first responders involved, the potential for RF interference, the potential for lost or degraded communications, and the number of types of Personal Area Network (PAN) devices in use. Participants in the research included firefighters, law enforcement, emergency management, Emergency Medical Services (EMS), National Guard, amateur radio and other agencies that make up the first responder community. While there is evidence of a proliferation of wireless devices in the first responder community, MERC discovered that these devices are slow to arrive into the hands of emergency personnel. To increase the number of types of wireless devices at each event, MERC worked with vendors and agencies to add additional devices beyond those typically used by participating agencies.

MERC participated in eight separate events and exercises during the research. Four of those events were major exercises with full RF analysis intended to meet the objectives of the study. The other four events were used to supplement the data collected and expand the research. The following table lists the exercises observed during this research.

Exercise/Event	Research Type	Date	Location	Number of Personnel
Rapid Intervention Team Training	Supplemental Research	10/10/2014	Warner Robins, GA	10
Georgia National Fair Mobile Command and Dispatch	Supplemental Research	10128/2014	Perry, GA	30
Georgia National Guard HRF/CBRNE	Supplemental Research	11/9/2014	Guardian Centers	90
National Guard HRF Full Scale Exercise	Primary Research	12/9 - 12/13/2014	Guardian Centers	300
Vigilant Guard	Primary Research	*3/6* – 3/9/2014	Georgetown, SC	2400
Hartsfield-Jackson ATL Airport Mock Disaster	Primary Research	4/15/2015	Atlanta, GA 100	100
Mock Subway Attack	Primary Research	4/28/2015	Guardian Centers	50
GEMA MCV Exercise	Supplemental Research	*5/5/2015*	Stone Mt, GA	100

Instrumentation

To perform the RF analysis, MERC designed a suite of sensor towers that were placed around the perimeter of the exercises and provided full coverage of the transmitters within the scene. A handheld spectrum analyzer supplemented the data collection by allowing engineers to quickly respond to suspected RF problem areas as they developed.

Human factors analysis relied on high-fidelity wireless microphones worn by selected tactical team members, video recording, and computer-based synchronization equipment to tie all data streams together. Questionnaires were completed before and after each exercise that included questions designed to help the researchers understand the experience level and cognitive loading of each participant.

Analysis

RF analysis included digital demodulation, signal strength and quality analyses. Human Factors analyses consisted of categorization of the modality of communication (interpersonal or radio), the type of loss (if any) and the category of communication involved.

Significant RF losses in multiple categories were found. These consisted of:

- Signal absorption and refraction due to absorptive structures such as buildings and subways;
- Excessive power levels from some transmitters;
- Noisy power generators; and
- Interoperability gateway setup errors.

The predominant type of RF problem observed during the exercises was from signal degradation due to building structures and the location of transmitters. Classical types of problems, such as intermodulation, co-channel and adjacent signal interference, were not significant and did not affect communications during these exercises. The researchers attribute this to frequency planning and proper licensing of frequencies in the jurisdictions.

Assessment of the cognitive and physical workload for the entire cohort of participants indicated moderate levels of workload and time pressure. Although tactical team leaders naturally experience increased workload due to the nature of their roles, radio communications loss did not significantly impact that load. However, researchers observed that first responders continued with mission tasks regardless of radio communication quality. While this did result in timely rescue and recovery of some victims, in two cases the first responders entered high-risk areas and notionally died because they were unaware of warnings transmitted via radio.

Recommendations

Based on observations and the results of the data analysis, the researchers determined a set of recommendations to be used by first responder communications planners moving forward:

- Planners of wide-band systems to be used by first responders should weigh characteristics such as security (user credentialing) and wider coverage areas (multihop).
- Develop a system of standard scenario templates and automated tools for placement of repeater stations to preserve line of sight communications. The researchers have conceived this as a system of “breadcrumbs” consisting of repeaters that are laid down by, or autonomously follow, first responders during ingress into a structure, which interferes with communication to preserve line-of-sight communications.
- Develop methods to enable tactical team members to identify when radio communication loss occurs to minimize the impact to operations.
- Develop a risk mitigation decision template for loss of radio communications. This work needs to include the development of training with alpha and beta testing on its use to enhance the safety of first responders.

Future Research

The results of this research highlight areas and topics where further research would greatly improve emergency communications and the effects of communications equipment on first responders.

- Research RF signal loss and degradation in urban and absorptive environments and make recommendations for anticipating and mitigating problem areas.
- Research the impact of ‘battle rhythms’ in the first responder tactical environment and investigate methods to recognize loss of situational awareness and cognitive overload in incident command.
- Research the potential for high levels of technology dependence in incident command to create new single point of failure risks when technology fails. Develop methods to mitigate this risk.
- Use previous research on cognitive workload in combat operations to design and conduct a research program to investigate cognitive workload impacts on first responders.

- Research and develop a prototype autonomous repeater swarm system (ground- or air-based) to follow first responders into a hazardous environment to maintain radio and PAN communications links in absorptive environments.

INTRODUCTION

Rapid advances in wireless technology and the increased demand for data capture and sharing has raised concerns that first responder mission critical communications will be adversely impacted by the growing number of devices that make up the first responder Personal Area Network (PAN). The risk that first responders will not be able to communicate effectively in emergency environments is a significant concern to the DHS S&T First Responders Group (FRG), especially during medium to large size incidents. Today's first responders average four or more PAN devices to perform their mission.

PAN devices include land mobile radios, cell phones, tablet computers, pagers, personal alert safety systems (PASS), global positioning system (GPS) devices and radio frequency identification (RFID) accountability systems. Standard first responder equipment is augmented by emerging technologies as those technologies are vetted. Emerging technologies include wireless body worn cameras (BWC), physiological monitoring equipment, biometric identification systems, electronic textiles, and location and tracking devices. To ensure mission success and personnel safety, PAN devices need to coexist without interfering with one another or being impacted by the surrounding environment.

This report presents the results of research undertaken for the FRG of DHS S&T Directorate to investigate PAN interference and compatibility issues for public safety personal protective equipment. The purpose of this research is to analyze first responder mission critical communications to determine the present and future potential for increased levels of RF interference to first responder PANs.

The Mercer Engineering Research Center (MERC) was tasked to evaluate the radio frequency (RF) environment during a minimum of four medium to large size exercises, which are defined as consisting of at least 30 first responders, with up to four PAN devices, operating within 30 feet of one another. The scope of this task was to collect RF data and conduct research and analysis on the threat of RF interference during multi-agency exercises, and then to make recommendations on ways that industry can help mitigate this risk in the future.

Guardian Centers, an 830-acre emergency response training facility in Perry, Georgia, was selected as MERC's partner and the site of two of the primary research events (Figure 1). Guardian Centers' training facility allows first responders to train in scenarios that include a multi-story building collapse, subway station terrorist attacks, flood scenarios, major multi-car pileups, active shooter, parking garage explosion and collapse, and large building fires.

Figure 1. Guardian Centers, Perry Georgia

Two other primary research events were included in the research approach: the U.S. Northern Command (USNORTHCOM) Vigilant Guard exercise in Georgetown, South Carolina and a mock plane crash exercise at the Hartsfield-Jackson Atlanta International Airport. These exercises provided a robust and diverse RF environment for data collection. A smaller exercise, the Georgia Mobile Command Post exercise located at Stone Mountain, Georgia, and three other supplemental research events were also included in the study.

BACKGROUND

First responders – police, firefighters, paramedics, emergency medical technicians and others – are tasked with saving lives and property when emergency situations arise. Since before the Revolutionary War, organized and trained units have been established to quickly and efficiently respond to fires, natural disasters, violent crimes and other catastrophic events. The 600 firefighters working in Victorian Era New York City with their horse-drawn, steam-operated pumpers were a vital necessity to prevent fires from devastating large neighborhoods of highly flammable wooden structures.

Communication and coordination among brigades at that time involved runners, flags, and speaking trumpets. Population growth and increasing density of cities fostered expansion and specialization among emergency response units over time, while advances in communications and other technologies supported vastly improved responsiveness.

When the terror attacks occurred in New York City on September 11, 2001, more than 900 emergency personnel from fire, EMS, police, and port authority agencies responded to the World Trade Center. They saved thousands of lives through coordinated action, professionalism and personal heroism. More than 400 first responders died in action during this event. According to the 9/11 Commission Report, problems with communication and coordination within and among responding groups on scene were identified as contributing factors for the extensive loss of life among responders.

The Department of Homeland Security (DHS) was set up in the wake of 9/11 to improve the nation's readiness against future terror attacks and other disasters. DHS has since led the effort to standardize emergency response processes and technologies nationwide through such things as the National Incident Management System (NIMS) and the anticipated National Public Safety Broadband Network, deployed as the First Responders Network (FirstNet).

One result of the assessment of the problems with the emergency response on 9/11 has been greater attention to developing procedures and technologies to improve tactical communications, situational awareness, inter-agency coordination and first responder safety. The development of trunked, digital radio systems has greatly improved the ability to maintain communications between tactical units and incident commanders. This is accomplished by increasing the capacity and distribution of operating channels.

Interoperability systems, such as the ACU-1000, can make communication and coordination among responding agencies much more fluid and efficient, which can greatly improve the development of a ‘common picture’ of emergency scenarios. Standard operating procedures issued through NIMS have improved the organization of emergency responses and the ability of commanders to account for all of the responding personnel within the tactical scene. More technology is being developed to provide automated accounting of personnel throughout the tactical environment, and to remotely monitor their individual physical status in order to further ensure first responders’ safety.

What happens to cause loss of life in emergency scenarios due to communications issues? Reports from after-action analysis of emergency response scenarios provide many different root causes; however, all fall into three broad categories: technology limitations, human limitations, and socio-technical problems.

Technology limitations cover a wide array of potential problems that first responders face when trying to wirelessly communicate. For instance, the radios carried by firemen into the burning World Trade Center buildings were unable to transmit to or receive communication from incident command on the ground outside due to signal power absorption through the building materials.

Human limitations arise when physical and cognitive stresses degrade the response of one or more elements of an emergency response team. This sometimes results in mistakes, decrements in radio-use discipline, loss of situational awareness and/or increased error rate.

Socio-technical problems result from organizational-level problems. They sometimes include failure to cooperate, failure to train effectively, failure to invest adequately in infrastructure such as signal repeaters, and similar problems. The most salient issues addressed in this report center on technical limitations and human issues.

A review of documents in the Homeland Security Digital Library (HSDL) was undertaken to quantify the contribution of each of these categories. Documents labeled as

"After-Action Reports," "Best Practices" and "Exercises and Lessons Learned" were downloaded and categorized. Of the approximately 80,000 documents in the HSDL at the time of the data pull (DHS, 2015), 369 were labeled as "After-Action Reports," 64 were labeled as "Best Practices" and 721 were labeled as "Exercises and Lessons Learned."

After removal of duplicates, corrupted files and non-document formats (audio/video), there were 1,009 documents eligible for further review. Each document was then evaluated for relevance to the current project. Documents were considered relevant only if they covered first responder involvement in an incident or an exercise that occurred in the U.S. between 2001 and 2015. All relevant documents were then coded for the following characteristics:

- Real incident or exercise.
- Type of event; e.g., fire, flood, hazmat, terrorism, etc.
- Setting (urban, rural or both).
- Mass casualties (simulated or real).
- Type of communication problems (technology issues, human issues or socio-technical issues).

Out of the full set of documents, 238 reports were classified as relevant to this research. A summary of the results of the HSDL literature review is provided in Table 1.

Table 1. Distribution of Relevant After-action Reports From HSDL

	Real or Exercise		
Type of Event	Real	Exercise	Total
fire	24		24
flood	29	8	37
hazmat	8	78	86
other	8	5	13
structural	4	9	13
terrorism	17	19	36
transportation	1	6	7
weather	20	2	22
Total	111	127	238

After further classification regarding the types of issues that were listed as problematic or needing improvement, the data (see Table 2) showed all three basic types of issues as major factors. Among real-world scenarios (n=111), technology issues played a role nearly as frequently as human factors limitations. Technology was less of an issue in exercises (n=127), as should be expected in planned events. Socio-technical limitations were listed as problem areas 96% of the time in real-world events.

Table 2. Distribution of Problems Identified in After-Action Reports From HSDL

	Identified Problems		
	Technological	Human	Socio-Technical
Real-world	82%	88%	96%
Exercise	67%	84%	90%

It is clear from this data documenting the real-world experiences of first responders that a mix of all three categories is common in large-scale emergencies. This reinforces the importance of the current research.

Communication Technology Issues

Public safety agencies provide valuable societal services in regards to protection of people, environment and properties against natural and man-made threats. Wireless mobile communication systems are indispensable tools currently at the disposal of public safety (PS) organizations. In particular, mobile radio is of prime importance in field operations to support the mobility of first responders. In the United States, the independent and autonomous nature of various agencies involved in public safety has led to the development and deployment of a host of wireless communication systems operating over a fragmented spectrum that are often inconsistent and not interoperable.

For many years, narrowband technologies were the dominant mode of PS communications. The first responders and various public safety agencies were limited to voice services and some low-rate data transmission, using channel bandwidths of 25 kHz, 12 kHz and 6.25 kHz on their private networks. At the same time, the development of commercial cellular networks offered a number of data services to the non-public service sector, such as messaging, email, Web browsing, picture transfer, video streaming and other wideband services [1].

The architecture for public safety communications has conventionally been similar to "pre-cellular" mobile communication that may be viewed as a "single-cell" system, where mobile users connect to a single high-power base station that provides radio coverage to a large zone. However, new systems for first responders are being developed and deployed that can be flexibly adapted depending upon the situation. These systems include jurisdictional area networks (JAN), incident area networks (IAN) and extended area networks (EAN) [1]. A JAN may operate as a single-cell or multi-cell system over a wide area, whereas an IAN can operate as an ad hoc network, temporarily set up to provide communication services for first responders during an emergency event [2].

The fragmented public safety spectrum includes bands from VHF, UHF and C-bands. In addition, some industrial, scientific and medical (ISM) radio bands are available for any "unlicensed" communications system, including for public safety links. However, if technologies such as Wi-Fi, which operate as unlicensed applications over ISM bands, are to be used for public safety, one has to be aware of the fact that these bands are very much affected by the congestion that is often present in emergency situations and thus they are susceptible to external interference that can make them unsuitable. Moreover, one has to be concerned about security issues when considering technologies such as Wi-Fi.

Types of Interference

There are many types of interference that can be present in a first responder environment and degrade communications. They include co-channel interference, adjacent signal interference, transmitter spurious emissions, intermodulation, multipath, power equipment noise, structural/materials interference, equipment setup interference and equipment failure interference.

Co-Channel Interference – Co-channel interference can occur if two or more devices transmit on the same frequency simultaneously. In conventional radio systems, if two first responders transmit at the same time, the signals are mixed in transmission and the result is garbled, or the device with the greatest signal strength is heard. These types of systems have been the backbone of first responder communications for decades, and users have learned through training and experience to listen to the radio traffic and determine a clear moment to "jump in."

Modern, digitally controlled radio systems mitigate this type of interference by operating as a master-controller and giving priority to individual transmitters. In essence, a first responder presses the push-to-talk (PTT), the system acknowledges with a ready tone and the transmission may begin. Other radios on that frequency are given a busy signal if the PTT is pressed.

Adjacent Signal Interference – Adjacent signal interference occurs if two devices transmit on different, but close, frequencies and the channel power from one signal falls within the channel of the next. When the Federal Communications Commission (FCC) ordered *narrowbanding* in 2013, channel spacing decreased from 25 KHz to 12.5 KHz. By law, old equipment must be removed from service or upgraded; however, for various reasons, some radios that are not compliant remain in service.

Transmitter Spurious Emissions – Transmitter spurious emissions are generated if a radio emits energy outside of its base band. Sometimes occurring in the form of unfiltered harmonics, these transmissions are typically unknown to the user until a problem occurs. Most commercial radio gear maintains excellent filtering due to stringent FCC regulations and required certifications. However, this type of interference is common when operating with older or damaged equipment.

Intermodulation – Intermodulation interference occurs if two or more different carrier frequencies are spaced such that the mixing of those signals produces sums and differences at an undesirable location in the frequency spectrum. For example, an amateur radio operating at 7.2 MHz in close proximity to a National Oceanic and Atmospheric Administration (NOAA) weather radio station at 162.475 MHz can cause problems for a nearby fire truck operating at 155.275 MHz (162.475 MHz – 7.2 MHz = 155.275 MHz).

Multipath – Multipath is a type of interference which occurs if the signal from a single transmitter can travel to a receiver using different paths. This can occur in different atmospheric conditions, different terrain and various building construction types. If the receiving radio receives more than one instance of a single radio's transmission and the signals are phase-shifted, multipath interference occurs.

Power Equipment Noise – This type of interference is common and occurs in different forms. If arcs form across damaged or loose connections, broadband emissions from electrical energy transmission equipment (e.g., transformers) can disrupt emergency communications if they are located nearby. Other similar types of power equipment noise occur when power generating equipment is not well grounded or when gaps in the generator components are not tightly controlled and shielded. This is a common form of interference that occurs when an agency selects low-quality power generators to be used in emergency response scenarios.

Structural/Materials Interference – This type of interference is caused by the type of building materials and land formations at the scene of an emergency. Different materials cause varying levels of attenuation of RF power. Similarly, different materials also compound the communication environment by introducing other types of interference, such as multipath and passive intermodulation. Underground operations of first responders, such as subway emergencies, cause significant reduction in radio communications due to the absorptive nature of the earth.

Equipment Setup Interference – This category of interference is one in which equipment is operating properly, but is improperly set up. Interoperability gateways such as Raytheon's ACU-1000, when hastily set up, can cause virtual elimination of radio groups that are tied together. For example, if the time-out controls are not properly adjusted in Raytheon's ACU-1000 interoperability gateway, the result is an infinite loop of carrier transmit-receive-transmit-receive. This phenomenon, called ping-ponging by first responders, destroys communication on both systems until the bridge is taken down and reset.

Equipment Failure Interference – This type of interference is not actually RF interference; however, during a stressful emergency situation, the result is the same. Uncharged batteries, corroded electrical connections and broken antennas are examples of radio equipment problems that commonly cause communication problems at an emergency scene.

Description of Public Safety Spectral Allocation

The frequency bands that are allocated, are being used on a temporary basis, or are otherwise potentially available for public safety communications systems are described in detail in the following subsections. They are summarized in tabular form in Appendix 8.

VHF Low Band (25-50 MHz)

The VHF Low Band located at 25-50 MHz is available for public safety communications, and is currently being used primarily by some state highway patrol and rescue squad agencies. The key advantage of this band is its extensive radio outreach. This band can provide coverage to a larger geographical area than any other band available for public safety communications. It is also more robust for traversing hilly terrain and penetrating heavily wooded areas than other available bands. However, VHF Low Band suffers from a number of hindrances. First and foremost, VHF Low Band is affected by various forms of interference such as "skip interference," as well as interference from man-made sources, including automobile ignition systems, motors, commercial power lines, etc., that are located in the vicinity of radio receivers. For this reason, VHF Low Band does not generally perform well in urban environments. Moreover, because of the long wavelength of the electromagnetic wave in this band, large antennas are required for efficient radiation of the signal. Any attempts to shorten these antennas for convenience or practicality results in radiation inefficiency and reduction of radio outreach [3].

VHF High Band (138-144 MHz / 148-174 MHz)

Owing to shorter wavelengths in this band, improvements in several aspects of propagation are observed in this band relative to VHF Low Band. First, the skip interference and the effect of manmade noise are substantially reduced. In fact, better penetration into metropolitan area environments is realized despite of the fact that frequency is higher and therefore the range is shorter. Furthermore, it is possible to use shorter antennae for efficient radiation in this band.

Due to these properties, VHF High Band has become the band of choice for many applications. Consequently, in many U.S. metropolitan areas, this band has become highly congested and interference from adjacent channels within the band has become a challenge.

Since the FCC has allocated this band for simplex or one-way transmission, point-to-point co-channel interference is particularly severe [3].

On January 1, 2013, the FCC issued an order that all applications, including public safety radio functions, operating within 150-512 MHz bands must change their systems from using 25 kHz channel bandwidth to 12.5 kHz channel bandwidth, or to a technology that achieves equivalent efficiency. The motivation was to enhance spectral efficiency and provide better spectrum access to both public safety and non-public safety users. Migration to 12.5 kHz efficiency technology is referred to as "narrowbanding," which will create additional capacity within the same radio spectrum to support more users. After January 1, 2013, licensees not operating at 12.5 KHz efficiency are in violation of the FCC rules [4].

UHF Band (450-460 MHz)

In comparison with VHF bands, the UHF public safety band (450-460 MHz) is virtually free from skip interference and almost immune to environmental electrical noise. At 450 MHz, the radio waves have shorter wavelengths than VHF bands. As such, they can easily reflect off of common hard surfaces. Thus, the UHF Band is often an excellent choice for penetrating into, and around, heavy building structures in urban areas. However, the UHF Band has more difficulty transmitting signals over hilly or irregular terrains than the VHF Bands. This implies that radio outreach over hilly areas can be significantly reduced. Moreover, absorption of the signal energy by foliage is more prevalent at UHF Band.

Narrowbanding, mandated by FCC in 2013, applies to the UHF public safety band as well. Thus, as in the case of VHF High Band, narrowbanding of UHF band ensures more efficient use of the available spectrum, higher ability to access the wireless network on the part of public safety users, and congestion relief as a result of the increased number of available channels. Public safety communities such as National Public Safety Telecommunications Council (NPSTC) and Association of Public Safety Communications Officials (APCO) have consistently supported the narrowbanding idea.

UHF T-Band (470-512 MHz)

The T-Band, located at 470-512 MHz, is a spectrum the FCC allocated for land mobile communications. Currently, parts of this band are also used to support critical public safety communications that provide regional interoperability among first responders in 11 major urban areas of the United States (Boston, Chicago, Dallas/Ft. Worth, Houston, Los Angeles, Miami, New York City, Philadelphia, Pittsburgh, San Francisco/Oakland and Washington, DC). It should be noted that each metro area uses only specific parts of the spectrum. In other words, the portion of the spectrum used by first responders is different from one metro area to the other.

A congressional mandate tasked the FCC to begin auctioning the public safety T-Band spectrum by February 2021 and clear all public safety operations from the band by early 2023. This public safety spectrum will be relocated over other bands to be determined later. NPSTC has expressed some concern about the feasibility of this spectral relocation and has requested a congressional reconsideration. "Given the lack of alternative spectrum, cost of relocation, disruption to vital public safety services, and likelihood that the spectrum auction would not even cover relocation costs, NPSTC believes implementing the T-Band legislation is not feasible, provides no public interest benefit and the matter should be re-visited by Congress." [5]

700 MHz Band

Certain segments of the 700MHz band (698-806 MHz) are allocated for public safety communications, and the remainder of the band is assigned for commercial wireless communication systems. The main characteristics of this band can be summarized as follows:

- Signals over this band have excellent propagation characteristics (relative to higher frequency bands) in the sense that they can easily penetrate buildings and walls.
- For less obstructed terrain, signals over this band can provide coverage to large geographical areas relative to the spectral bands of higher frequencies.

In July 2007, the FCC issued an order which will allow the Public Safety Spectrum Trust (PSST) Corporation to enter into leases of spectrum usage rights with commercial licensees or operators of the spectrum adjacent to the public safety broadband spectrum (the 700 MHz D Block). The FCC Second Report and Order (R&O) included rules for the D Block auction winner(s) to build a nationwide public safety shared wireless broadband network that will be paid for by the auction winners and not by the public safety community or the taxpayers.

The FCC rules are intended to ensure that public safety will have priority access in emergencies and that the network will be continually refreshed with the latest technical improvements paid for by public safety's commercial partners. Subject to the capacity and other requirements of the public safety community, the Public Safety Broadband Licensee (PSBL) will make the remaining public safety capacity associated with the PSBL broadband spectrum available to the commercial licensees or operators, who will provide the bulk of the financial support for the system through their revenues.

In 2008, the FCC auctioned licenses for segments of 700 MHz band (775-788 MHz) for commercial mobile applications. This spectrum has since been used by mobile service providers for broadband services such as smartphones and tablets [6].

Nationwide Broadband Network for Public Safety and the "FirstNet"

On February 22, 2012, the "Middle Class Tax Relief and Job Creation Act," nicknamed the "Spectrum Act," was signed into law. Following the congressional enactment of the "Spectrum Act", the FCC was authorized to take on the following initiatives. First, the FCC allocated the band over 758-763 MHz/ 788-793 MHz ("D-Block") for the formation of a nationwide broadband network for public safety. Secondly, the FCC was directed to create the First Responder Network Authority (FirstNet) as an independent entity of the U.S. Department of Commerce. The plan is to create a single interoperable platform for public safety agencies and first responders for day-to-day critical and emergency communications where the FirstNet is tasked with management, licensing and deployment of nationwide public safety broadband communication systems.

This is the first time that the United States Congress has allocated spectrum and provided funding for the creation of a wireless communications network for public safety. The FirstNet is charged with exploring modern and existing telecommunication technologies to establish a core network dedicated to public safety. In order to create a nationwide public safety network, each state and territory is required to design their own radio access network (RAN) that connects them to the nationwide FirstNet core network. Since May 2013, FirstNet has been consulting with various local and state governments to assist in developing requirements of their own RAN.

The total bandwidth that is allocated for FirstNet consists of 20 MHz over the 700 MHz Band. This includes 10 MHz of spectrum already allocated for nationwide public safety broadband communications, which is located over 763-769 MHz/793-799 MHz (of which 2 MHz is used for guard band), and 10 MHz of reallocated "D Block" over 758-763 MHz/ 788-793 MHz.

Although the objectives and the requirements of a nationwide broadband wireless network for public safety have been identified to some extent, the network architecture for FirstNet and the RANs are yet to be determined. Within the next few years, various technologies will be evaluated against the required technical characteristics and strategic objectives of public safety broadband network and in accordance with a broad range of selection criteria. Some have argued that broadband mobile communications face a number of technical and economic challenges. They have cautioned that the current paradigm of selecting a communication scheme based on dedicated technologies, dedicated networks and dedicated spectrum no longer constitutes the best approach for introducing a PS mobile broadband network, and hence new innovative solutions are needed [7]. On the other hand, there are some indications that the worldwide community, including Project 25 (P25) and Terrestrial Trunked Radio (TETRA) users, is evaluating an all-LTE-based broadband network for public safety [8].

Narrow Band Channels for Public Safety Community

The 700 MHz band also houses 12 MHz of spectrum (769-775 MHz/799-805 MHz) for narrowband PS communications systems. With recent FCC narrowbanding to 6.25 kHz, this portion of 700 MHz Band is divided into 1,920 one-way (simplex) radio channels operating as 960 two way (duplex) channels. The FCC allows the licensees to combine two to four contiguous channels to form 12.5 kHz and 25 kHz bandwidth channels, subject to compliance with spectrum usage efficiency requirements [6]. The narrowband segment of the 700 MHz Band is separated from the broadband section by 2 MHz of guard band.

800MHz Band

Traditionally, the 800 MHz band (806-899 MHz) has been home to three applications:

- All generations of commercial cellular phone systems (1G, 2G, 3G and 4G with AT&T, Verizon, Sprint, U.S. Cellular).

- Private mobile radio systems such as Specialized Mobile Radio (SMR) and Enhanced Specialized Mobile Radio (ESMR), such as Sprint (Nextel) Direct Connect.
- Public safety wireless communication systems.

Segments of the 800 MHz Band have been the primary spectral bands used by first responders for critical public safety communications. These narrowband systems have been the main means of effective communications between dispatchers and their corresponding first responders, or among the first responders themselves. One issue of concern for public safety wireless communication systems operating in the 800 MHz band has been the increasing levels of interference from commercial cellular radio and private mobile radio systems functioning in the same band. The interference problem in the 800 MHz band is caused by adjacent channel interference of fundamentally incompatible communication technologies. On one hand, the commercial mobile wireless systems and private mobile radio, with their cellular architecture, are using multi-cell and low-power base station antennas. On the other hand, the non-cellular public safety mobile communications systems are using single base stations with high-power, high-tower antennas in the classical pre-cellular mobile communications configuration. This configuration requires a favorable location within the desired coverage area. These two types are mixed within closely located bands of frequencies [9].

To combat the effects of this harmful interference, the FCC has ordered a reconfiguration ("rebanding") of the 800 MHz band, moving public safety licensees to lower segments of the band and commercial cellular networks to higher segments, separated by an Expansion Band and a Guard Band [10]. The narrowband Public Safety Communication System is located at the lower part of the 800 MHz band (779-805 MHz). Nominally, the Expansion Band is located over 815-816 MHz/860-861 MHz; however, in certain areas of the southeast U.S., the Expansion Band is located over 812.5-813.5MHz/857.5-858.5 MHz, and the Expansion Band is 813-813.5 MHz/858-858.5MHz within a 70-mile radius of the city of Atlanta.

Enhanced Specialized Mobile Radio (ESMR), followed by commercial cellular phone band, occupies the bands 817-849 MHz and 862-894 MHz. However, these bands are separated from the public safety bands by the Extension Band and Guard Band, which protect the public safety bands against interference from private mobile radio (PMR) and cellular phone to a large extent.

The rebanding process is an FCC-driven plan, which consists of both long-term and short-term components. According to the short-term plan, technical standards defining unacceptable interference in the 800 MHz band were identified. For the long-term solution, the FCC ordered the reconfiguration of the 800 MHz band to address the identified root cause of the interference by separating generally incompatible technologies. Nevertheless, regardless of what type of signal processing techniques and communications protocols these unharmonious technologies are incorporating, one might expect some residual interference remaining even after completion of rebanding.

4.9 GHz C-Band Public Safety Spectrum

In 2002, the FCC allocated 50 MHz of spectrum in the 4.94-4.99 GHz range, known as the 4.9 GHz band, for fixed and mobile services excluding aeronautical mobile applications. The band was allocated to be used in support of public safety. The stipulation is that non-traditional public safety entities, such as utilities and the federal government, may enter into sharing arrangements with eligible traditional public safety entities to use the band in support of their missions regarding homeland security [11].

This is a relatively new band for public safety communications and, at least in one project, this band has been used to successfully demonstrate many public safety applications, including email, database query, file download, remote video monitoring and streaming video [12]. One issue with this C-band spectrum is its propagation mode. With the short wavelengths associated with this band, relative to VHF and UHF bands, the signal rapidly attenuates. This implies that this band may be suitable for public safety services that require extensive bandwidth but short-distance coverage, such as wireless personal area networks (WPAN) and wireless local area networks (WLAN), but not practical for wireless wide area networks.

ISM Bands

The Industrial, Scientific, and Medical (ISM) bands, defined by the International Telecommunication Union Radiocommunication Sector (ITU-R) at the global level, generally are for non-communications applications of RF radiation. It should be noted that individual countries' use of the ISM bands may be different. This is mostly due to variations in national radio regulations. Communication devices in general, public safety communication equipment in particular, are allowed to operate over some parts of these bands. In the United States, the FCC has permitted unlicensed communications operation over three ISM bands located at 902-928 MHz, 2.400-2.4835 GHz and 5.725 to 5.875 GHz. However, communication devices using the ISM bands must tolerate any interference from ISM equipment. In other words, there are no protections against interference from co-allocated applications.

The ISM bands occasionally share allocations with unlicensed and licensed operations; however, due to the high likelihood of harmful interference, licensed use of the bands is typically low. Security issues are another concern when ISM band are used for communications applications.

License-free ISM bands have been used for a number of wireless communications networks. In particular, WPAN (based on Institute of Electrical and Electronics Engineers (IEEE) 802.15 standard) and WLAN (driven from IEEE 802.11 standard), have extensively used ISM bands. For instance, Bluetooth and ZigBee, examples of WPAN, operate over the 2.4 GHz ISM band. However, resource planning and bandwidth allocation cannot be guaranteed over ISM bands.

As it has been mentioned already in this report, there are no protections against interference in ISM band, aside from the fact that the FCC limits the output power of the systems that might operate over these bands. For instance, it is well known that domestic and commercial (restaurant) microwave ovens operate near 2.45 GHz. Table 3 provides the list of original ISM bands defined by ITU-R, along with some comments on how they are being used.

Table 3. ISM Bands Originally Defined by the ITU-R

Frequency Range	Bandwidth	Notes
6.765-6.795 MHz	30 kHz	Subject to local acceptance
13.553-13.567 MHz	14 kHz	Global use for non-communications applications
26.957-27.283 MHz	326 kHz	Global use for non-communications applications
40.66-40.70 MHz	40 kHz	Global use for non-communications applications

Frequency Range	Bandwidth	Notes
902-928 MHz	26 MHz	Region 2 (United States)/ non-communications applications/ may also be used for unlicensed public safety communications
2.4-2.5 GHz	100 MHz	Global use for non-communications applications / May also be used for unlicensed public safety communications
5.725-5.875 GHz	150 MHz	Global use for non-communications applications / May also be used for unlicensed public safety communications
24.00-24.25 GHz	250 MHz	Global use for non-communications applications
61-61.5 GHz	500 MHz	Subject to local approval
122-123 GHz	1 GHz	Subject to local approval
244-246 GHz	2 GHz	Subject to local approval

APCO-25

In the United States, Project-25, also known as P-25 and APCO-25 (Association of Public-Safety Communications Official International), is the dominant narrowband standard for digital wireless communication that is used for PS applications. APCO-25 is essentially a suite of standards for public safety communications, used by federal, state and local PS agencies in the United States and Canada. APCO was developed, in collaboration with Telecommunications Industry Association (TIA) with four objectives in mind: improvement in spectrum efficiency in comparison with the legacy analog FM LMR networks; providing enhanced equipment functionalities; offering open system architecture to promote competition between various vendors; and allowing effective, efficient and reliable intra-agency and interagency communications [13].

APCO-25 continues to be a dominant PS communication technology in the United States, as well as several parts of the world, in part because of its adaptability to users' changing needs. The first phase of P-25 features radios with 12.5 kHz band capable of operating in analog, digital or mixed modes. Phase II of Project-25 features radios operating with 6.25 kHz bandwidth, which was developed in anticipation of FCC's narrowbanding mandate [14].

APCO-25 Phase I system applies FDMA access method with Continuous 4-level FM (C4FM) modulation scheme. Phase II configuration may operate with either FDMA or TDMA access technologies with Compatible Quadrature Phase Shift Keying (CQPSK) modulation and supports encrypted communication. APCO-25 provides voice and limited data rate communications up to a maximum of 9.6 Kbits/s. It further provides a rich set of services, including messaging, group calls, broadcast calls and others. APCO requires a fixed infrastructure, which can be seriously degraded or destroyed in a rural area in the event of a large natural disaster [13].

A Phase III development for APCO-25 is also contemplated, whose initial agreement was ratified in the year 2000. The ETSI and TIA are working collaboratively on APCO Phase III, which is known as Mobility for Emergency and Safety Applications (MESA). This project addresses the need for high-speed data transmission for public safety applications and promotes effective, efficient, and advanced specifications and applications towards PS broadband communications needs [15].

Table 4 lists parameters and the key signal processing techniques used in Physical Layer and Link Layer of APCO-25 networks [16].

Table 4. Key Signal Processing Techniques and Parameters of APCO-25 Networks

Access Technology	Modulation Scheme	Symbol Rate (Bud Rate)	Nyquist Filtering	Error Correction Coding	Frequency Bands of Operation	Required BW
Phase I: FDMA Phase II: FDMA/ TDMA	**Phase I: C4FM** **Phase II: CQPSK**	Phase II 4.8 kilo Symbols per Second	Raised Cosine with Roll-Off Factor 0.2	Hamming Golay BCH RS Trellis	**VHF**: 136-174 MHz **UHF**: 403-512 MHz 746-806 MHz 806-870 MHz	Phase I: 12.5 kHz Phase II: 6.25 kHz

Satellite Networks

The key advantage of satellite networks in public safety communications is that they do not rely on an existing terrestrial infrastructure; therefore, in the event of a large natural disaster they remain functional. The second attractive feature of satellite networks is the fact that they can transmit signals in a variety of frequency bands, such as UHF, L-Band, C-Band, Ku Band and so on. In terms of radio coverage, satellite systems are capable of covering quite an extensive area. Fixed terminals can provide data rates in the order of 1.5 Mbits/s, whereas mobile terminals offer data rates in the order of 256 Kbits/s [13]. Mobile Satellite Services (MSS) provide two-way phone services (voice and data) to global users who are on the move or in remote locations. MSS terminals may be carried or be installed on trucks, automobiles, ships or even airplanes, with communication maintained while the vehicle is in motion. As such, MSS terminals can be an important asset in the PS domain by providing almost full coverage with the additional benefit of mobility. A specific scenario in which satellite networks can be particularly suitable, because of their independence from terrestrial fixed infrastructure and their wide area of coverage, is the case of large natural disasters where satellite communications can be used to deploy an ad-hoc network in the area struck by a disaster [17].

Advancing Towards LTE-Based Technologies: FirstNet

FirstNet is a new broadband public safety communication network built over Band Class 14 (758-768 MHz for DL & 788-798 MHz for UP), which will allow high-speed public safety communication services that cannot be supported by LMR-based technologies. It is planned to provide reliable, functional, safe and secure broadband services at "optimal levels of operational capability at all times" for public safety. FirstNet is envisioned to be based on LTE standards, a proven reliable technology tested through four generations of cellular communications. This is the first time that the public safety communication network is based on commercial standards, where the benefits of lower costs, economies of scale and advanced communications capabilities are exploited [18].

Four distinct layers are defined for the LTE-based FirstNet. First is the ***Core Network***, which is a packet network providing the users with a single interoperable platform at the national level. As such, the core network is responsible for data switching, processing and reformatting information, storing and maintaining data, and so on. The second layer is the ***Radio Access Network*** (RAN), which functions very similar to that of commercial cellular systems. RAN consists of base station infrastructure that connects to user devices. The next layer is the ***Transport Backhaul Network*** composed of the links that carry user traffic, such as voice, data and video, from the base stations to the core network. The final layer is ***Public Safety Devices*** consisting of all the user access points that will send and receive information over the network. These devices include everything from smartphones to laptops, tablets, dongles and a wide variety of specialty devices that will be developed for FirstNet users [18].

The emerging high-speed, low-latency LTE-based technology can represent a viable alternative and a complimentary solution for PS communication. The public safety organizations may be using different types of PS networks. For instance, in the United States, a mixture of LMR-based radio systems, FirstNet and commercial telecommunication networks might be used by different public safety agencies. The narrowband LMR-based devices provide mission critical voice capability with limited data rates. However, through deployment of high-power base stations and handsets, wide area of coverage can be achieved with LMR technologies.

On the other hand, while first responders can still rely on LMR devices for mission critical voice services, FirstNet can provide a high-speed network that can equip them with real-time update capabilities [15]. The commercial cellular networks are all IP-based and can assist in providing PS services; however, as was mentioned earlier in this report, they are vulnerable to network congestion due to high inbound and outbound traffic when an incident occurs. This sort of congestion can disrupt communication services.

Despite all limitations of LMR-based PS networks, they are bound to remain in use by various public safety organizations. Furthermore, different agencies will continue using these devices even though they may not be interoperable and the first responders of one area cannot, and in many cases would not want, to communicate with their colleagues in the neighboring area. FirstNet, however, will be a broadband network that has the potential of becoming a common communications thread providing a national interoperable web.

Human Factors Issues

Usability and Training Issues

Usability problems in first responder radio communication systems can occur at all levels of the Incident Command Systems (ICS): command & control; dispatch and support staff distributed in the system at-large who are using radio terminals; the Communications Unit Leader (COML) or Communications Unit Technician (COMT); and first responders at the tactical edge. Each of these groups uses different radio communications devices, including hand-held portable, mobile command post systems, vehicular mobile radios or desktop units, which will involve different usability challenges.

The COML is responsible for both the operational and technical aspects of communications during an incident, while the COMT is tasked with determining the appropriate radio channels and talk-groups to be used, installing and maintaining incident radios, interference mitigation, programming and deployment of cache radios, etc. [22] The usability problems encountered by COML/COMT are likely to occur due to poorly designed physical and graphical user interfaces (GUI). Some examples of this are listed below:

- Hard to read labels or incomprehensible acronyms and icons on the hardware that may result in the improper configuration, connection and setting of the interoperability controller.
- Poor or lack of feedback about system status or issues on the interoperability controller's user interface (absence or sub-optimally designed LED status lights, voice prompts, tones, etc., that may go unnoticed).
- Difficult to understand information architecture and menu structure, unintuitive icons, etc. of the GUI.
- A mismatch between users' mental model of the interaction flow with the software vis-à-vis what is required (or constrained) by the logic of the program. (This problem may be encountered on interoperability controllers, radio service software and customer programming software (RSS & CPS) used by COMLs and COMTs.)

These usability problems are likely to be exposed or exacerbated due to lack of training and inadequate or unavailable documentation, particularly under stressful situations, such as when setting up ad hoc field communications following a natural or manmade disaster.

The usability problems encountered by tactical radio users or operators mostly pertain to the ergonomics aspects of the physical user interface and to poor or inadequate feedback (e.g., absence of tones or visual cues). Some examples of usability problems encountered by radio users include:

- Inaccessibility of buttons and knobs, particularly when donning personal protective equipment (PPE) such as fire gloves (see Figure 2).

- Inadvertent activation of the emergency button.
- Incomprehension of speech (muffled) by the receiver (when transmitter speaks from under the self-contained breathing apparatus (SCBA)).
- Inability to read the information on the display under bright sunlight or glare.
- Inconsistent methods to change channels or talk-groups among radios that may belong to the same or sister fleets. For example, COMTs may program radios where fallback channels or talk-groups have to be accessed by manipulating controls other than the channel knob (See Figure 3).
- Inadvertent activation of the on/off knob and channel knob when radio is worn on the belt holster due to insufficient resistance. This can sometimes be caused by vehicle seat belts or when entering or exiting tight spaces or vehicular cockpits.

Figure 2. Inaccessibility of the Emergency Button Due to Small Size When Used With Thick Fire Gloves [23]

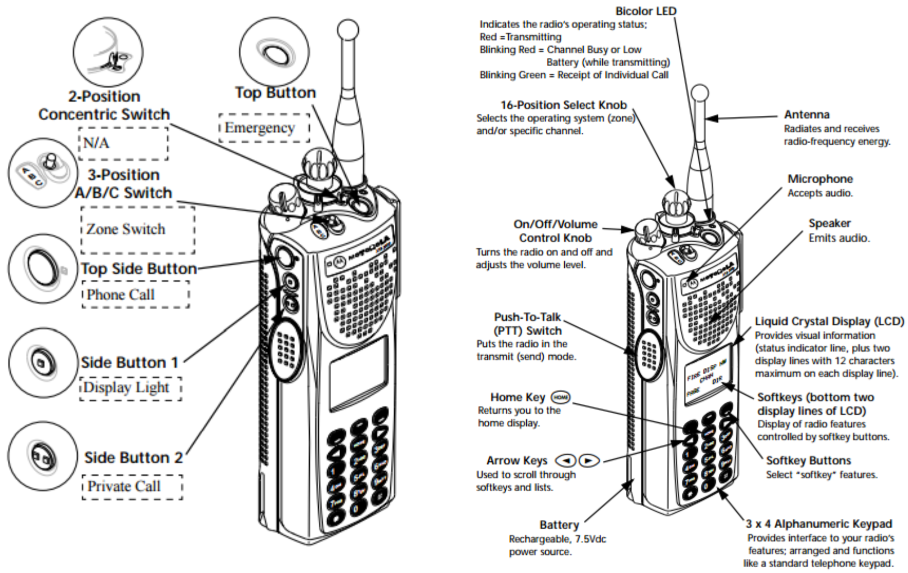

Figure 3. COMTs Can Assign Operational Features to Different Controls [24]

Insufficient training, particularly of radio users at the tactical edge, may reduce the effectiveness of the radio communications, which, in turn, may compromise safety and security of first responders and civilians alike. Some common issues that might be manifested on the incident scene or fire ground due to insufficient training are listed below:

- Poor radio discipline (e.g., unwanted banter or low priority communications tying up the radio channel and blocking more important communications).
- Initiating or transmitting inappropriate mayday or man-down calls, when the situation is not warranted, tying up the entire radio system.
- Not knowing which channel or talk-group to switch to when the primary channel is down.
- Not knowing how to switch to the secondary or alternate channels when the primary channel is down or when a command is issued to switch to another channel for continuing communications.
- Not knowing what specific auditory tones mean; e.g., low-battery tone versus channel busy tone.

Sociotechnical Issues

Sociotechnical system issues that result in breakdown of radio communications have been known for a long time. Examples of such causes are outdated equipment and lack of technical and organizational interoperability. L.J. Hettinger highlighted this issue by analyzing the breakdown in radio communications during the 9/11 disaster that resulted in the loss of lives of both FDNY firefighters and civilians [25]. He illustrated the socio-technical continuum from organization to team to individual, as shown in Figure 4, to present the range of factors contributing to the outcome.

The operational requirements for responding to an emergency are determined by a number of considerations, as described in the NIMS protocols: Preparedness, Communications and Information Management, Resource Management, Command and Incident Management, and an incident's size and complexity. The size and complexity of an emergency situation has a direct bearing on the workload, on stress levels, and on the patterns, intensity and volume of communications among different stakeholders. Again, Figure 4 shows that stakeholders can be considered a continuum of all personnel involved, from first responders at the tactical edge to the senior management higher up in the Incident Command System (ICS) structure.

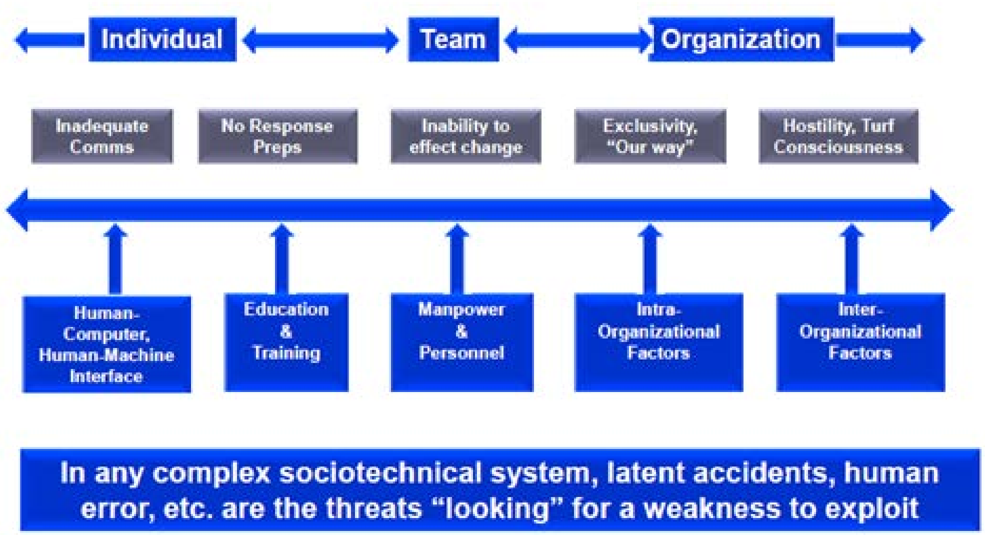

Figure 4. Sociotechnical Continuum. Image Adapted from Hettinger, 2011

A mismatch in the capabilities of the first responders to the requirements of an emergency situation will exacerbate their workloads and stress levels. For example, even a simple Type 5 incident (See Appendix 1 for NIMS incident classifications), such as a vehicle fire, may pose a serious challenge to a first responder who lacks adequate knowledge, skills or equipment to bring the situation under control. In this case, communication with a commander or an expert cohort is a key enabler for the first responder to act effectively until help arrives.

Human factors such as stress and workload may not only be affected by, but may also contribute to, a breakdown in communication and performance, which can further impair performance. For instance, poor training, time stress, danger-induced emotional arousal and modulation of cognition, high workload, etc., may negatively affect different stages of communication and performance. The results are numerous: the inability to perceive an auditory signal due to excessive cognitive load (auditory exclusion), the inability to perceive a visual stimulus due to excessive cognitive load (inattentional blindness), breakdown of thought and speech processes, poor radio discipline, and inability to adhere to standard operating procedures, such as closed-loop communications.

The classical model of communication theory presented by C.E. Shannon and W. Weaver shown in Figure 5 provides a means for conceptualizing the scope of human-centered communication problems [26]. In this model, communication errors may result from any one of the following reasons:

- The SENDER may choose to send the wrong information to the right person or the right information to the wrong person.
- The SENDER may not semantically encode it accurately with proper phraseology.
- Due to an error of commission, the SENDER may choose the wrong CHANNEL.
- Technical or ambient noise may corrupt the signal, even if it is on the right channel.
- The RECEIVER may decode it wrongly and misinterpret the message, either on his own or with any one of the above serving as contributing factors.

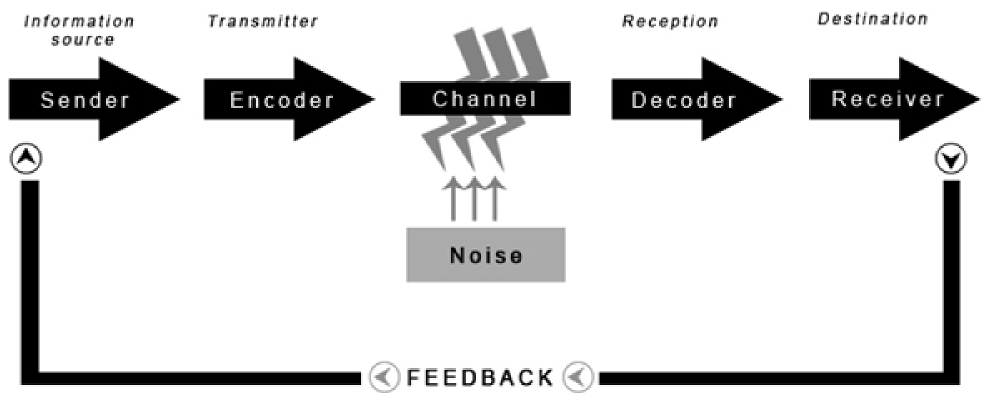

Figure 5. Shannon-Weaver's Model of Communication

In mission critical domains, fast and accurate communication is essential to sense-making and decision-making, which are the key elements of situational awareness. Situational awareness is a function of macrocognition, which allows first responders and incident commanders to develop shared mental models of the emergent scenario.

Macrocognition is a term coined by P.C. Cacciabue and E. Hollnagel to describe the cognitive functions that are performed in natural (versus artificial laboratory) decision-making settings [27]. In contrast, microcognition, typically studied in the lab, is the set of building blocks of cognition, the processes that are invariant and serve as the basis for all kinds of thinking and perceiving [28]. Microcognition encompasses such elementary components as making the decision to communicate, determining the content and style of communication (semantics, syntax, phraseology), identifying cues within messages (Hit, Miss, False Alarm, Correct Rejection), and other basic perceptual and (micro) cognitive processes.

In a naturalistic setting such as emergency response, macrocognition is initiated as a result of the following conditions [28]:

- Decisions are typically complex, often involving data overload.
- Decisions are often made under time pressure and involve high stakes and high risk.
- Goals are sometimes ill-defined, and multiple goals often conflict.

- Decisions must be made under conditions in which few things can be controlled or manipulated; indeed, many key variables and their interactions are not even fully understood.

Moin Rahman conceptualized such emergency scenarios as non-equilibrium situations that have five key descriptors: volatility, uncertainty, complexity, ambiguity and time (VUCA+T). He defines them as follows [29]:

- **V**olatility: the situation is in non-equilibrium and rapidly changing. It is difficult to predict or project future states.
- **U**ncertainty: due to insufficient information, inability in sense-making or lack of control, decisions must be made in a state of uncertainty.
- **C**omplexity: this can arise due to data overload (high volume, velocity and variability in data coming from multiple channels), or from difficulty in creating a reliable mental model of the system versus ground truth.
- **A**mbiguity: the many key variables and interactions within the system are not fully understood.
- **T**ime: temporal stress on the tactical team and the ICS to quickly bring the situation under control to minimize and mitigate loss.

Research on situational awareness [30] and sense-making [31], particularly with regard to perception, comprehension and mental models, has provided only limited constructs with which to understand the coupling between micro and macrocognitive processes. In the context of the current study, it is important to measure the impact of radio communications in tactical environments relative to all of the internal and external inputs to the first responder, how those microcognitive processes influence the loss of operational or tactical situational awareness, and the initiation of procedural or operational errors in emergency response.

Operationalizing the cognitive and performance processes of the first responder is the preliminary step needed to make such measurements. An input/output model of human performance was developed for this purpose, based on theories of multiple attentional resources [32]. The underlying principle of these theories is that attention is a limited resource used within specific channels, such as visual channels, speech/language channels and cognitive processing channels. As more channels of attention are engaged at once, a first responder will experience an increasing cognitive load and loss of performance. When the limits of an individual's span of control are reached, some channels disengage, leading to such things as inattentional blindness. Figure 6 illustrates the input/output model. In the diagram, external sensory inputs are yellow or red, attention resources are purple and outputs are green.

Radio communications, shown in red in Figure 6, is separated from verbal communications even though it takes up a portion of the first responder's auditory channel, too. This is because RF signals make up a large part of the personal area network traffic, though it is unclear what proportion of overall communication traffic it represents. It is also clear that radio traffic, typically with the incident commander, has a different level of prioritization than ambient verbal traffic and will thus absorb more attention when radio communications are required in the scenario.

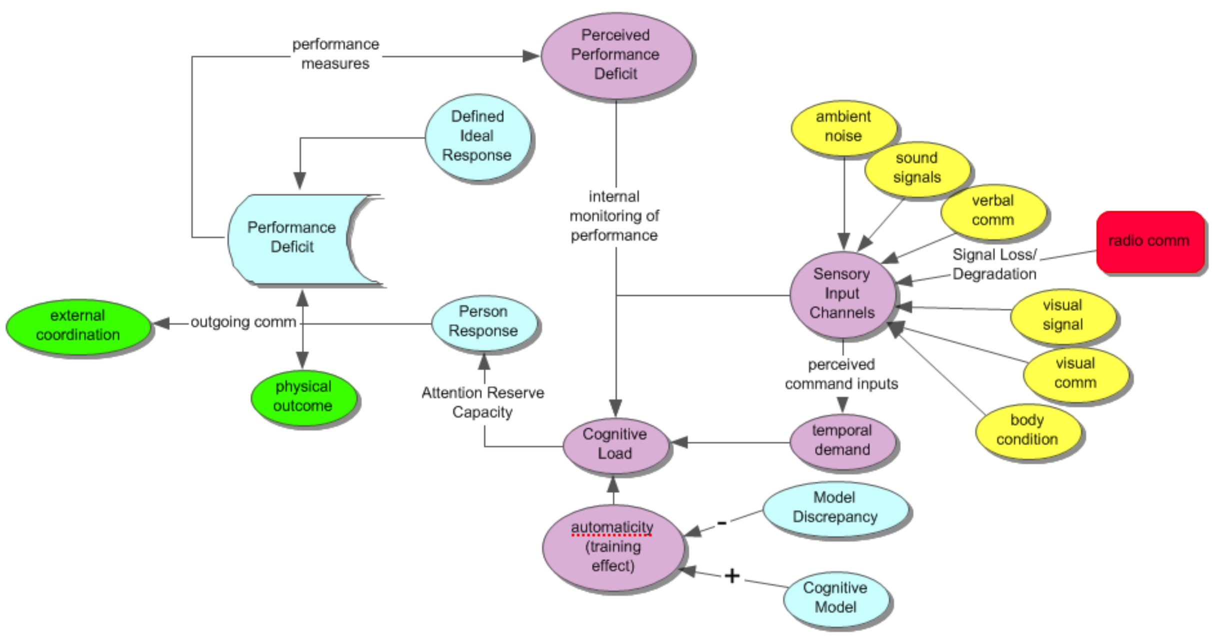

Figure 6. Illustration of Microcognitive Input/Output Model of First Responder

The automaticity channel shown in the illustration represents the release of attention-controlled processing resources through over learning. Thus, as long as the mental picture of the emergency event matches the cognitive model developed through training and experience, the first responder can apply attention resources to other activities. As the scenario looks less predictable, however, more attention must be applied to determining what should be done, and the cognitive workload thus increases.

METHODOLOGY

The purpose of this research is to analyze first responder mission critical communications to determine the present and future potential for increased levels of RF interference to first responder PANs. The emphasis is on the impact that signal loss has on first responder workload and on situational awareness at the tactical and command levels. The input/output model in Figure 6 illustrates the following requirements for measurement design:

- Measurement of the interference in the communication channels, which causes RF signal degradation;
- Measurement of the information present on communication channels;
- Measurement of the responders' physical condition (fatigue/work output);
- Measurement of the responders' training and experience; and
- Measurement of the responders' performance and temporal pressures during emergency response scenarios.

Planned Exercise versus Real-world Scenarios

In alignment with the goal of the research, the researchers designed experiments to collect and analyze communications interference on the ability of first responders to communicate and share data effectively during emergency situations. The researchers determined that the required measurements could be obtained during planned medium- and high-intensity, multi-agency first responder exercises rather than real-world disasters.

There are advantages to participating in planned exercises. The most important advantage of collecting data during controlled exercises is the ability to participate in preplanning meetings to identify and collaborate with the various agencies involved in the training. This enabled the researchers to:

- Understand the experimental environment.
- Allow for controlled and uncontrolled variables.
- Evaluate the baseline signals environment prior to the experiment.
- Adjust the scenario and instrumentation if required to ensure sufficient data collection.
- Coordinate with various industry partners to introduce new and emerging technologies for use by the first responder community into the scenario.

Measuring Information Transmission and Loss in Human Communications

First responder radio communication includes only analog radio, digital radio and cellular transmissions of language-encoded information. Although this ignores wirelessly transmitted non-language data, such as health status monitoring and location data, these are not currently significant sources of transmitted information in emergency response scenarios. The anticipated human factors effects of this additional input to future first responders and incident commanders will thus be addressed in the discussion of the results of this research.

Information transmission is defined as the delivery of appropriate and correct information as quickly, unambiguously and reliably as possible, while still allowing maximal comprehension by the receiver in a given environment. Components of transmission include: clarifying transmissions, confirmatory re-transmission, re-transmission due to lack of response, correcting re-transmissions, transmitter verification of receiver (correct) comprehension, receiver acknowledgements and requests for clarification of previous transmission.

Repetition, corrections, requests for repetition, verification and requests for clarification are used as measures of error in communication. The types of error may range across five different types, as discussed earlier in the Shannon and Weaver [26] model (see Figure 5 and related text). Errors due to technological noise or ambient noise interacting with electronic noise are used for calculation of error rate due to RF signal degradation or disruption. All sources of error are grouped in order to facilitate calculation of overall error rate.

RF signals may be disrupted or degraded in different ways. Signal disruption is the loss of signal power to the point where a carrier frequency cannot be reliably detected by receiving equipment. It can be caused by loss of transmitter power, excessive distance from transmitter to receiver or path-specific absorption of signal power by intervening materials. Signal degradation, on the other hand, is defined as a reduction in signal information due to the psychoacoustic effects of additive noise power. This can derive from three analog sources: transmission, transmitted and environmental. It can also arise from digital information losses.

Transmission noise is a background signal implicitly transmitted due to atmospheric effects, spectral interference from other RF sources or equipment effects (i.e., power lines, generators, etc.) that result in auditory noise to the receiver speakers. Transmitted noise is ambient sound picked up by the transmitting microphone that is sent together with the intended information. Environmental noise is ambient sound in the area around the receiver. Digital information loss occurs in wireless communications (i.e., digital radio systems, cell phones, Bluetooth equipment, etc.), due to data packet collisions or data packet displacements in systems using transmission-layer protocols that lack packet checking.

The broad range of potential sources of information loss make it critical not only to log instances of information loss, but also to classify the causes of this loss in order to quantify the scope of each type of problem as it affects the first responder. The sources of radio and interpersonal voice transmission loss are categorized as shown in Table 5.

Table 5. Sources of Information Loss When Transmitted Verbally, Through Radio Or Interpersonally

Loss Category	Type of Problem	Cause	Notes
Ignored	Human factors	Inattention or distraction	Loss of information leading to delayed or incorrect tactical action
Incorrect	Human factors	Auditory substitution	Loss of information (in the absence of proper standard operating procedures) or delayed transmission
Unintelligible	Technical (Environmental)	Ambient audio noise power or frequency interfering with radio output	Messages can be lost due to ambient or transmitted audio noise

Loss Category	Type of Problem	Cause	Notes
Channel Selection	Human factors	Incorrect selection of talk channel	
Radio Failure	Technical or Human factors	Electronic or mechanical malfunction	Human factors problem if preventable
Busy channel	Socio-technical factors	Excessive traffic preventing calls	Mitigated by appropriate frequency planning
Path absorption	Technical (Signal disruption)	RF signal absorbed by intervening materials before reaching receiver	
Environmental Noise	Technical (Signal degradation – Transmission)	Magnetic or electrical field effects on RF signals	
Frequency Crosstalk	Technical (Signal degradation – Transmitted)	Primary or harmonic radio signal frequency close to the RF signal of interest	
Noise Floor	Technical (Signal degradation – Transmitted)	RF receiver de-sensitization from high-power transmission source	

Research Questions and Definition of Variables

Four key research questions must be answered to determine how the first responders will be affected by RF signal loss and degradation within PANs during emergency response. The research questions and associated hypotheses (H) are:

1. Within the scope of current and future wireless communications technology used by first responders at emergency scenes, what are the causes of RF signal loss and degradation?

    a. H1a: RF carrier signal amplitude loss is measurable in predictable types of emergency scenarios.

    b. H1b: Analog RF signal spectral interference is measurable in predictable types of emergency scenarios.

    c. H1c: Digital signal loss (i.e., packet loss, channel preemption, system setup) is measurable in predictable types of emergency scenarios.

2. How much information is lost due to each of the sources of signal loss and signal degradation?

a. H2: Analog and digital radio signal loss or degradation has a measurable effect on information loss in the tactical environment.

3. What proportion of the total information flow at the tactical level is lost due to radio traffic losses?

   a. H3: Analog and digital radio signal loss or degradation represents a significant percentage of the total data bytes communicated among squad members and with the incident commander.

4. How much is first responder workload, both physical and cognitive, increased for a given amount of radio signal loss or degradation, compared to the total loss from all types of signals?

   a. H4a: Subjective measures of perceived exertion and workload increase with increasing information loss.

   b. H4b: Subjective measures of perceived exertion and workload for squad radio man are measurably increased over other members of squad without radio communication responsibility.

Given these research questions, the researchers determined that synchronous collection of RF and human factors data was required to provide a basis for correlating signal loss and degradation to information loss in the tactical scene. The key independent variables include:

- RF amplitude and location for specific frequencies and time;
- RF amplitude and frequency spectrum for specific time;
- Radio channel capacity and demand at specific frequency and time;
- Number of instances of wireless channel data loss, total RF information transfer;
- Total information transfer;
- Total information loss, RF information loss; and
- Cohort perceived exertion, workload.

The dependent variables are determined by the individual hypotheses. Table 6 lists the different types of variables for each hypothesis, and how they are measured.

Table 6. Independent and Dependent Variables for each Hypothesis and How They Are Measured.

Hypothesis	Independent Variable	Dependent Variable	Measurement
H1a	RF amplitude and location for specific frequencies and time	Identified information loss due to signal loss at specific time	Audio identification of information loss evaluated by an electrical engineer (EE) as signal loss, and classified by cause
H1b	RF amplitude and frequency spectrum for specific time	RF primary channel signal-to-noise ratio	Audio ID of information loss evaluated by an EE as degradation, and classified by cause
H1c	Radio channel capacity and demand at specific frequency and time	Identified information loss due to limited channel capacity or data packet collision	Audio ID of information loss evaluated by an EE as digital data loss, and classified by cause
H2	Number of instances of wireless channel data loss, total RF information transfer	Information errors	Counts of information transfer and information errors from audio recording, classified by cause
H3	Total information transfer	Information errors	Counts of information transfer and information errors from audio recording, classified by cause
H4a	Total information loss, RF information loss	Perceived exertion, workload	Psychophysical and subjective ratings of workload and exertion
H4b	Cohort perceived exertion, workload	Radioman perceived exertion, workload	Psychophysical and subjective ratings of workload and exertion

The researchers expected wide variability in verbal data transmission, both interpersonally and via radio. For example, there is little difference in the amount of information transmitted by the following sentences:

- Sergeant Jones, I would like your team to move forward together toward the objective.
- [said to Jones] Move out!

In digital systems, measures of information transfer are given as 2 bytes per digital word, where a word is the smallest unit of meaningful information handled by the instruction set of a central processing unit (CPU). If we assign a value of 2 bytes to each spoken or tacitly understood word in the previous spoken sentences, the total data transfer for one is 3.5 times the other. The researchers used a normalization technique that assigns information value to each verbal transmission to control the variability of data flow versus information transmission.

In addition to the confounding effect of verbosity, the researchers expected training and experience to have a strong effect on the workload each subject experiences in a tactical environment. These confounding variables were collected from each subject in the tactical scene and used to statistically test the degree of covariance with workload in order to determine the amount of effect developed from RF signal problems.

Experimental Design

The researchers chose naturalistic experimental methodology for this study. This methodology enabled the researchers to concurrently collect RF and human factors data with more ecological validity than would be possible in a laboratory setting.

Naturalistic experiments involve identifying or creating realistic scenarios in which the independent and dependent variables of interest are likely to change. The researchers then develop data collection protocols for those scenarios. This type of experiment promotes greater fidelity in measurement of the complex human responses involved in emergency situations. It also reduces the demand-effect on human performance, since the subjects have no insight into what is being measured. A significant limitation in this type of experiment is the lack of control over the independent variables, making future replication by other researchers more difficult.

Radio Frequency Instrumentation Design

Even though the most prevalent frequency bands used by the modern first responder community are VHF (approximately 150 MHz – 160 MHz) and UHF (approximately 450 MHz – 900 MHz), the potential exists for emergency environments using a wider range. With many segmented bands allocated to public safety, the full first responder RF spectrum is broad. It currently ranges from HF (3 MHz and up), when an emergency scene is supported by Amateur Radio Emergency Service, to approximately 5 GHz with the presence of Wi-Fi, Bluetooth and other wireless devices.

The researchers selected a suite of sensor equipment that was capable of performing spectral analysis throughout the wider band.   The size and transportability of the equipment were deciding factors that were as important as the technical specifications of the equipment.

Emergency scenes are dynamic. Their size and scope change as a scenario progresses, therefore the equipment that was used to analyze the RF environment had to be easily modified, moved and reconfigured as required.

The researchers assembled the sensor components into a set of four remote sensing towers. Each tower was approximately 8-feet tall including the antenna, and included a remote spectrum analyzer (RF Sensor), power supply, receive antennas (GPS and broadband RF) and networking components. The towers were designed to be set up around an emergency exercise, providing full coverage of the scene (see Figure 7).

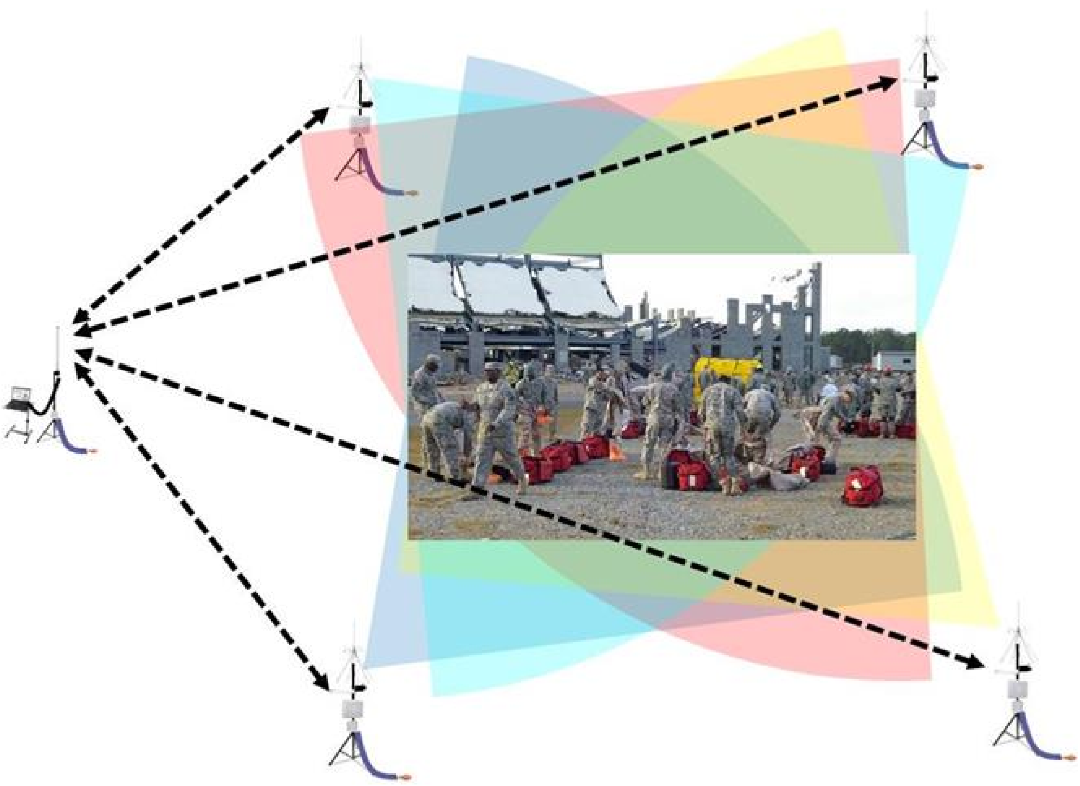

Figure 7. Conceptual Diagram of Sensor Towers Surrounding an Emergency Scene

A laptop was interconnected with the four RF sensor towers (Figure 8) by a wireless private network. The computer was a commercial grade laptop with spectral analysis software installed (Figure 9).

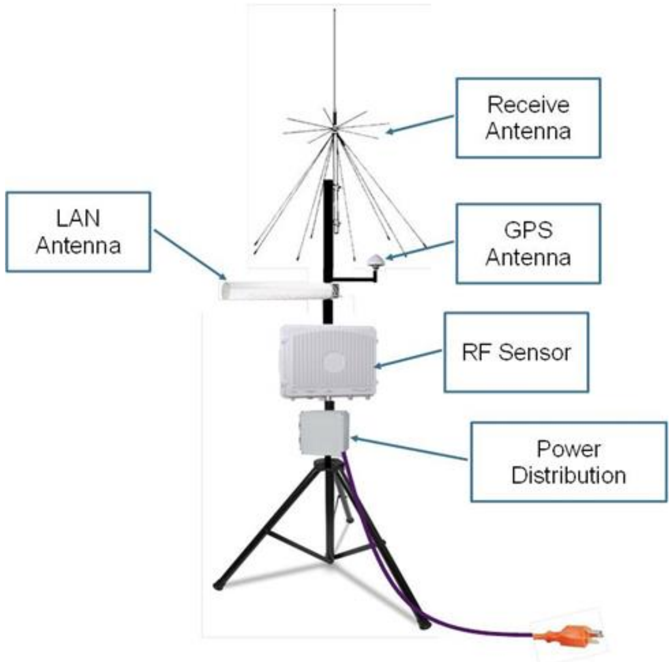

Figure 8. RF Sensor Tower with Antennas and LAN Connectivity Devices

Figure 9. Central Processor/Data Collection Laptop Connected Via Wireless Network

System Component Descriptions

N6841A RF Sensor

The Keysight N6841A RF Sensor shown in Figure 10 was selected as the core of the sensor suite because it is enclosed in a weatherproof case and is designed for wide area, close-proximity signal monitoring, detection and location. It has Ethernet TCP/IP network connectivity, which allowed for a networked distribution of sensors around an emergency scene.

Figure 10. N6841A RF Sensor

The specifications of the N6841A RF Sensor are:

- Environmentally rugged IP67-rated weatherproof enclosure. Sealed unit with no moving internal parts.
- Small footprint for ease of setup and teardown.
- Wideband RF receiver with 20 MHz to 6 GHz frequency range.
- Digital IF bandwidth adjustable up to 20 MHz.
- Signal look back memory (4.8 secs at 20 MHz BW).
- I/Q streaming up to 1.9 MHz bandwidth for recording or off-board signal processing.
- Integrated GPS for sensor location and time synchronous applications.
- High-precision measurement synchronization and time stamping.
- AM/FM demodulated audio streaming.
- Two Type-N RF input ports (switched) for multiple antennas.

Broadband Receive Antenna

The Diamond D3000N Super Discone Antenna was selected as a general purpose receive antenna because of its easy setup and excellent coverage of public safety bands.

Figure 11. Diamond D3000N Broadband Super Discone Antenna Mounted to a Tripod Stand

The specifications of the D3000N are:

- Receive Coverage: 25-3000 MHz.
- Gain: 2 dBi nominal.
- Height: 67".
- Connector: Type N.
- Element Phasing: Wideband Discone.
- Materials: Stainless Steel.

Wi-Fi (Wi-Fi) Radio

The researchers selected the Ubiquiti Bullet M2 Zero-Variable Outdoor airMAX Radio to allow long distance networking between RF sensors. The 600 mW power and self-contained design seamlessly interfaced the LAN output of the sensors across long spans of the exercise scenes.

Figure 12. Ubiquiti Bullet M2 Wi-Fi Radio

The specifications of the Ubiquiti M2HP are:

- Networking Interface: 1X10/100 Base-TX (Cat 5, RJ-45) Ethernet.
- RF Connector: Type N Male.
- Operating Temperature: -40 to 80C.
- Max Power Consumption: 7 Watts.
- Power Method: Passive Power over Ethernet.
- Operating Frequency: 2412-2462 MHz.

LAN Yagi Antenna

The L-Com Model HG2415Y Yagi antenna was selected to transmit the network data around the exercise scene. The Yagi is designed for directional applications. This particular antenna's lightweight plastic housing and adjustable mounting bracket allowed MERC to direct its beam easily using line-of-sight, point-and-shoot techniques.

Figure 13. L-Com Yagi Wi-Fi Antenna

The specifications of the L-Com HG2415Y are:

- Frequency: 2400-2500 MHz.
- Gain: 14.5 dBi.
- -3 dB Beam Width: 30 degrees.
- Impedance: 50 Ohm.
- Max. Input Power: 50 Watts.
- VSWR: < 1.5:1 avg.
- Lightning Protection: DC Short.

LAN Omni Antenna

The ALFA Network AOA-2412 was selected as the base station antenna to receive LAN traffic from the four RF sensors.

Figure 14. ALFA Network Omni Wi-Fi Antenna

The specifications of the AOA-2412 are:

- Frequency: 2400-2500 MHz.
- Gain: 12 dBiV.
- VSWR: <1.5:1.
- Connector: Type N Female.
- Polarization: Vertical.

N9912A FieldFox Handheld RF Analyzer

The Keysight FieldFox is a battery-powered portable spectrum analyzer with a frequency range up to 6 GHz. With built-in interference analysis software, the FieldFox is able to provide spectrogram and waterfall analyses enabling the researchers to monitor the RF spectrum and watch for signals that might be sources of interference.

Figure 15. Keysight N9912A FieldFox Analyzer

The specifications of the N9912A FieldFox Analyzer are:

- Frequency Range: 100 kHz to 6 GHz.
- Resolution Bandwidth Range: 10 Hz to 5 MHz.
- Accuracy: +/- 0.35 dB typical.
- Weight: 6.6 lbs. including battery.
- Dimensions: 11.5"x 7.4"x 2.8".
- Environmental: MIL-PRF-28800F Class 2.

Signal Processing Laptop and Software

All data collected during each emergency exercise was stored on a commercial grade laptop. Keysight analysis software packages were installed on the laptop and provided for communication with the RF sensors, storage of spectral data and detailed analysis of RF information.

The researchers selected the HP EliteBook 8570w because of its compatibility with Keysight equipment. Keysight Software (see Figure 16) that was installed on the laptop included:

- Signal Surveyor 4D automated high-speed, high-resolution RF searches across single or multiple radio bands processing energy that met detection criteria. It was also used manually as a high-speed spectrum display with the ability to task audio handoff receiver, modulation recognition, recording, direction-finding and emitter location measurements. It worked exclusively with the N6841A RF sensor hardware.
- Spectrum Visualizer software provided a quick display of the full range of the RF Sensor and powerful, yet simple tools to perform spectrogram and waterfall analysis. This tool was used to quickly scan the RF spectrum for activity before focusing with other software tools.
- Keysight Vector Signal Analysis software allowed for detailed demodulation and analysis. It allowed the researchers to explore the characteristics of RF signals and determine parameters such as error rates, etc., in APCO digital transmissions.
- Keysight Sensor Management Tool was the core application running on the laptop.

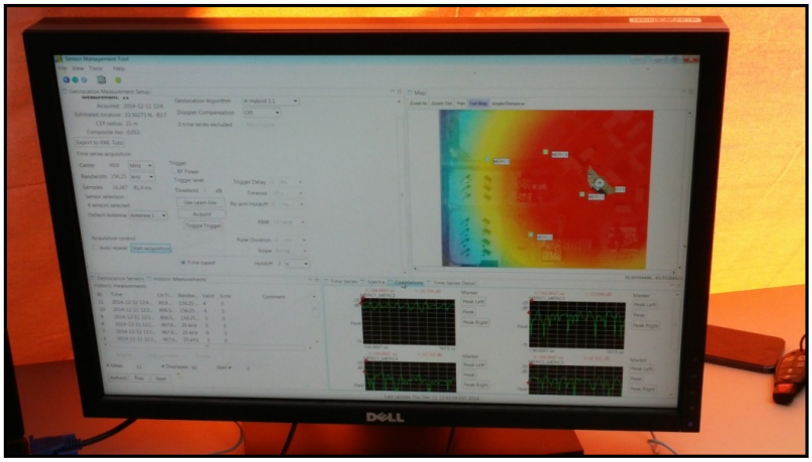

Figure 16. Keysight RF Analysis Software

Human Factors Instrumentation Design

Audio feeds from first responders and incident commanders were developed using wireless lavalier microphones and transmitters. Countryman E6 ear-worn, omnidirectional microphones were used to pick up all audio in the immediate environment around the tactical team leaders, including radio traffic, ambient noise and verbal traffic. As shown in Figure 17, the microphone booms were formed into a semicircle in order to place the microphone in the ear canal on the radio receiver side, so recording levels would be equivalent to the sound levels perceived by the first responder.

Figure 17. The Mounting and Orientation of the Lavalier Microphone

Field testing showed the audio sensitivity was sufficient to record clear speech outdoors from individuals speaking at conversational levels (approximately 40 dBA) 10 feet away from the microphone. Each microphone was connected to a Sennheiser EW300 transmitter, which was mounted on the clothing of the first responder in a manner that would least interfere with movement or function (see Figure 18).

Figure 18. The Mounting and Orientation of the Transmitter

The transmitters and receivers operate on ultra-high frequency (UHF) bands between 518.2 MHz and 556.1 MHz. Specific frequencies were selected for each channel in order to avoid interference from ambient noise or competing signals. High-gain and omni-directional antennas were used with the Sennheiser receivers to enhance the reception on channels expected to have problematic reception. Figure 19 shows a photograph of the RF and HF data monitoring stations being assembled prior to an underground exercise.

Figure 19. Radio frequency (left) and human factors (right) data monitoring stations for the subway exercise

GPS time synchronization of the human factors data with the RF data was provided using an Ambient Clockit ACC501 time controller with a GPS receiver. The time was output by the Clockit as longitudinal time code (LTC), which is an audio-encoded time signal that can be synchronously mixed as a separate channel in the audio recording.

A PreSonus AudioBox 1818 VSL 8-channel audio mixer/pre-amplifier was used to integrate the Sennheiser audio feeds and the GPS LTC feed. One AudioBox channel was dedicated to recording with a dynamic microphone from a radio receiver set to the tactical communications channel. This provided full reception for all traffic, regardless of RF signal problems on the Sennheiser feeds, and provided a more complete record of total radio traffic throughout the scenario.

Video of tactical teams was recorded during each scenario in addition to the audio feeds. The purpose was to capture any gestural data transmitted between tactical team members, as is typically used in situations where ambient noise levels make verbal transmission ineffective. The video records also provided visual orientation and reference for post-hoc analysis of data from the audio feeds.

GPS synchronization was needed for the video recordings, though the timestamp resolution required for the video was much less (on the order of seconds) than for the audio and RF data (on the order of 0.1 seconds). This was achieved by recording the GPS clock reading at the start of each recording, then using the elapsed time reading on the camera to provide real-time clock synchronization. The schematic diagram shown in Figure 20 illustrates the full instrumentation setup used for each scenario.

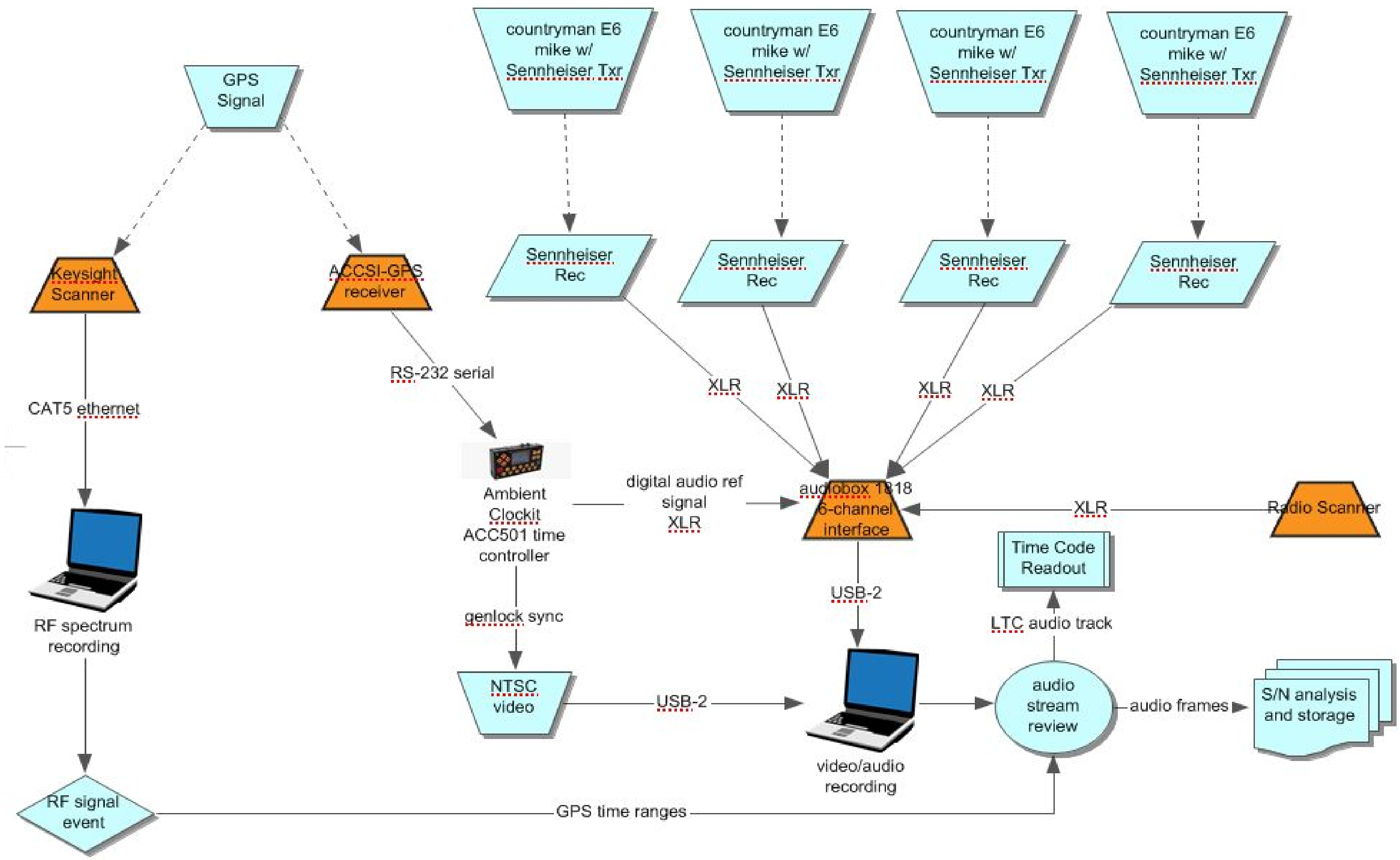

Figure 20. Schematic Diagram of RF, Audio and Video Instrumentation

Measurement of the factors affecting workload for first responders during each scenario was accomplished using a mix of psychophysical instruments and self-rating questionnaires. Copies of these instruments can be found in Appendix 2.

The Borg CR10 rating of perceived exertion was used to gather data on first responders' physical workload. This is a well-studied instrument developed originally as a linear-scale, ranging from 6 to 20 whose responses correlate with oxygen consumption and aerobic demand. The category-ratio (CR) scale version, which uses a range from 0.5 to 10, was developed in the 1990s to provide better level anchoring for wider ranges of activities involving physical exertion and simpler instruction to subjects [33].

First responders were asked to rate their state of exertion before they began their role in the scenario, then again after they had completed their tactical activity. Ideally, the Borg CR10 responses are intended to be gathered as temporally close to the exertion as possible. Since we could not interrupt the scenario to ask questions, the first responders were asked to rate their maximum exertion and their current physical exertion after the tactical activities, providing a total of three data points per responder.

The National Aeronautics and Space Administration (NASA) Task Load Index (TLX) is another widely used instrument [34]. It is a multi-dimensional questionnaire, commonly used to provide a rating of overall workload based on user ratings along six subscales: mental demands, physical demands, temporal demands, personal performance, effort and frustration. Each of the dimensions is presented as a visual assessment scale divided into 20 equal segments, and anchored with dichotomous descriptors (e.g., high/low). The scales are intended to be pairwise-compared by subjects before the exercise in order to develop a set of weights for each subscale rating. Early testing showed this was too complex to effectively implement in a naturalistic environment. The subscale ratings were thus left unweighted.

A high-velocity human factors (HVHF) questionnaire based on information developed from Moin Rahman was used to fill in workload measures along the VUCA-T dimensions as mentioned earlier [29]. These dimensions are complementary to those of the NASA TLX in some areas, i.e., time demands, mental demands and physical demands.

Rahman adds dimensions of complexity, confusion and predictability that have been found to impact error rate and situational awareness in emergency situations [35]. Seven-point Likert scales, set up as zero-centered differentials, were used to provide ratings on the six dimensions. Likert scales are typically formatted in levels showing degrees of agreement or disagreement as responses to verbal statements. They typically range from strongly disagree to strongly agree. Dichotomous descriptors were again added to anchor the ratings along each subscale. In addition, self-rating questions about each individual's level of comfort in the current role within the scenario and post-hoc ratings of communication quality were included.

Testing Protocols

The researchers collected as much preliminary data as possible on the size, scope, technologies, activities and locations of each exercise. Using this information, the researchers planned staging areas, personnel distribution, instrumentation setup, power distribution and addressed other logistical demands of the data collection.

Setup and field testing of all instrumentation and testing protocols were performed one to three days in advance of each exercise, if possible. The locations of the Hartsfield and Stone Mountain exercises were inaccessible for preliminary setup and testing. Although they offered less scope for data collection, particularly human factors data and RF geolocation, there were no problems with the quality of the RF data collected.

RF Testing Protocol

RF data collection required a minimum of one researcher, with setup help as required depending on the scope of the exercise and the time constraints. The preparation and execution of the testing protocol began in the weeks ahead of the event and are described here as a 4-stage process.

Stage 1: Frequency Research

In advance of an exercise, the researchers met with the event planners and requested information regarding the proposed frequencies, systems and talk-groups. In addition, the researchers completed a matrix of expected equipment to be used by exercise participants. MERC took that information and added it to the local transmitter frequencies found in the Radio Reference Database (www.radioreference.com). This list of frequencies allowed the RF researchers to set up the data collection equipment to expect certain spectral activity. For example, Table 7 is an excerpt from the list of expected frequencies at the December 2014 exercise with the National Guard.

Table 7. List of Expected RF Channels to be Used During the CERF-P Exercise at Guardian Centers

Frequency (MHz)	Agency	Description
399.9250	National Guard	HRF C2 CMD
396.8750	National Guard	HRF A&L/ JSG
397.1250	National Guard	CBRNE TF/ CERFP CMD
395.1875	National Guard	Communications
409.3375	National Guard	WMD CST
300.3000	National Guard	JISCC Repeater
2412-2462	National Guard	Wireless LAN
451.8625	Guardian Centers	Trunked Digital Comms Frequencies
452.4375	Guardian Centers	Trunked Digital Comms Frequencies
456.8625	Guardian Centers	Trunked Digital Comms Frequencies
457.4375	Guardian Centers	Trunked Digital Comms Frequencies
458.8625	Guardian Centers	Trunked Digital Comms Frequencies
2412-2462	Body Worn	Bluetooth from Sensor to Base
154.5700	Body Worn	Vital Signs Transmitter to Base
854.5625	Houston County	Trunked Digital Comms Frequencies

Frequency (MHz)	Agency	Description
854.7875	Houston County	Trunked Digital Comms Frequencies
518-560	MERC	Wireless Microphone System
2412-2462	MERC	Wireless LAN Connection

Stage 2: Site Survey

Whenever possible, researchers visited the exercise site prior to an exercise to identify locations for the RF sensors, the RF data collection laptop and power sources for each. For some exercises, the researchers were not able to perform a site survey. Instead, the researchers used satellite images from Google Earth to effectively determine sensor locations and lines of sight.

The figure below shows the Google Earth image of the Georgetown, South Carolina Airport, which was used during Vigilant Guard in March. Note the location of the four RF sensors.

Figure 21. Georgetown, SC Airport RF Sensor Locations
(image courtesy of Google Earth)

Stage 3: Set up and Testing

Researchers set up RF sensor towers, the data collection laptop, generators and network connections, tables, chairs and tent prior to exercises. The data collection laptop was set up in a tent or vehicle, usually co-located with the human factors equipment (see Figure 22).

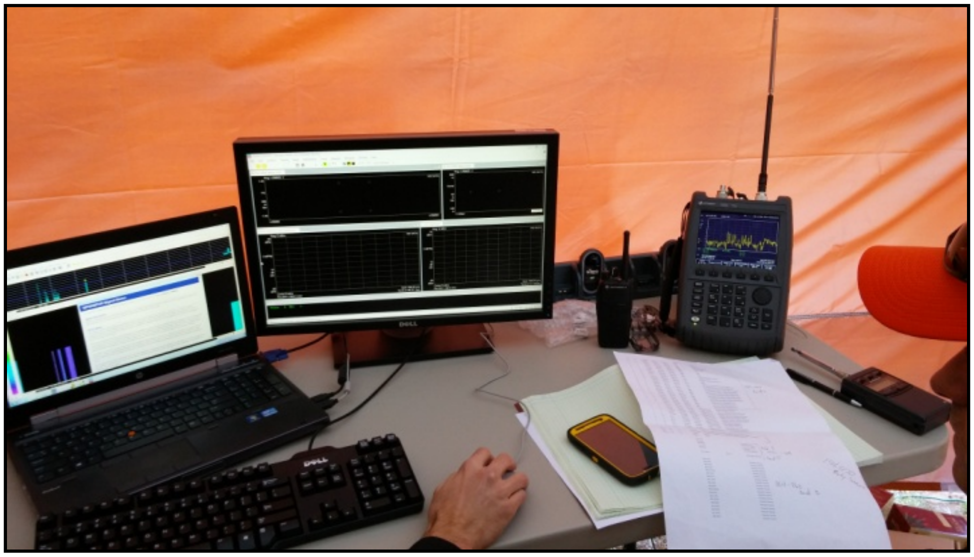

Figure 22. RF Data Collection Laptop Set Up in the Field at an Exercise

Sensor towers were positioned around the exercise venue in a manner that allowed full coverage of the scene and maintained line-of-sight from each sensor to the base station (see Figure 23). Line-of-sight was required due to the wireless LAN used to interconnect the sensors. These placements were designed in advance of the exercise.

If electricity was not available to each sensor within a 100 feet cord distance, portable generators were used to power them. Following the complete setup of the network of sensors, the system was tested by running the Sensor Management Tool software to verify connectivity with each sensor. Each sensor was then tuned to a local broadcast radio station to verify that each was receiving RF data properly.

Figure 23. Researcher Setting Up RF Sensor Tower at the Vigilant Guard Exercise

Stage 4: Exercise Data Collection

Before the start of an exercise, a sweep of the RF spectrum was performed to determine ambient RF energy present. Potential sources were AM/FM radio stations, TV stations, cellular, paging systems, commercial and public safety radio systems, and other spectral energy such as noise from lighting systems and generators.

This information was stored as baseline RF data. In addition, the researchers tuned the sensors (using Vector Signal Analysis software) to the frequency bands of the first responder agencies and stored each as a setup file. This allowed the researcher to quickly retune the equipment to another agency based on audio heard over the scanner receiver.

Each frequency used by the participants in an exercise was then monitored on a rotating basis to look for signs of interference. As other team members gleaned interference possibilities from their human factors work, or from networking with participants, the RF equipment was tuned to those frequencies to monitor for anomalies.

Because of the dynamic nature of an exercise, it was not possible to perform real-time demodulation analysis of digital transmissions. This decision was made to ensure that the instrumentation was collecting data during the entire exercise. If digital radios were in use, spectral measurements of the digital data were collected for post-processing.

Geolocation calibration was performed on transmitters at a known location to verify the proper operation of the equipment. After calibration, if spectral monitoring identified signals of interest, the geolocation function of the RF sensors system was used to calculate the probable location of the transmitter. Figure 24 shows the geolocation of a transmitter at the Vigilant Guard exercise.

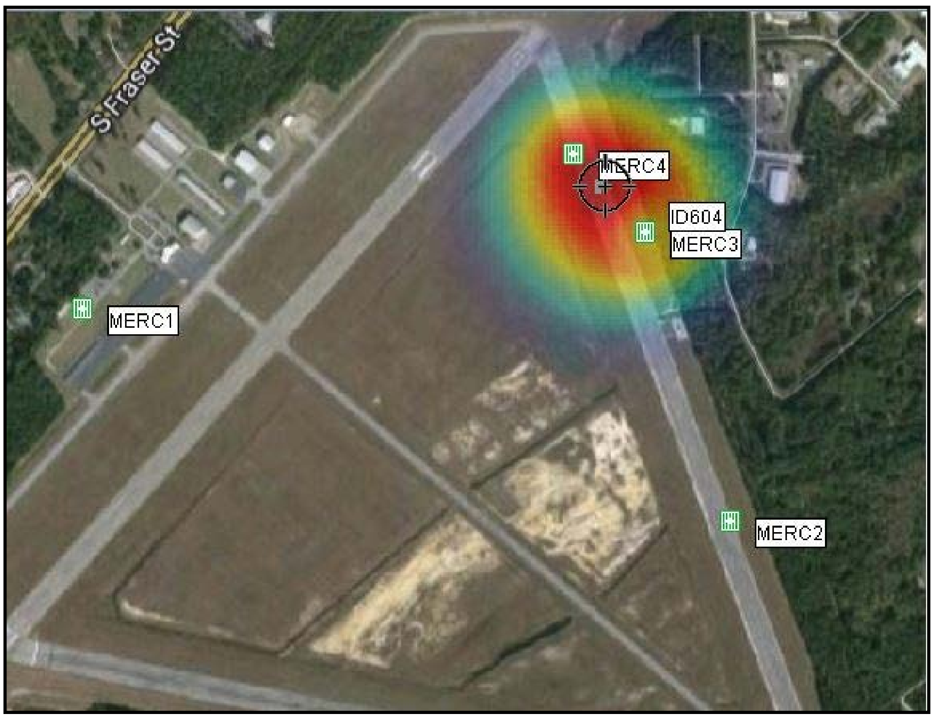

Figure 24. Geolocation of a Transmitter at Vigilant Guard Exercise

The Keysight FieldFox handheld spectrum analyzer was used to supplement the stationary RF sensor suite towers. If a moving participant needed to be monitored, a researcher was assigned to shadow the first responder and continue to collect spectrum data using the FieldFox. Because the FieldFox has a broadband sweep capability, it was also used to “sniff” the electromagnetic environment for RF sources and capture center frequencies. That information was then used to tune the RF sensor system.

Human Factors Testing Protocol

Human factors data collection required a minimum of three (3) researchers, with extra help recruited as needed for questionnaire data collection. The testing protocol during the exercise was designed as a 3-stage process: set up/test of audio and video feeds; instrumentation and pre-tactical questionnaire data; and de-instrumentation and post-tactical questionnaire data. See Appendix 3 for an example of a complete human factors testing protocol.

Stage 1: Set up/Test

One researcher was assigned as data monitor, whose job was to set up and monitor audio recording channels and to log all tactical activity being recorded. A recording filename was selected in the Studio One recording software that provide the mixing control interface to the AudioBox mixer.

All Sennheiser channels were turned on and checked for sound level and interference. Transmission frequencies were adjusted as needed to eliminate interference. The Clockit time controller was set to send out the GPS LTC on an audio channel. The sound level for this channel was adjusted and the time signal was checked using time code reader software. Test recordings were stored as separate files, with the filenames and test time logged in the research notebook.

The planned first responder groups (Search & Extraction, SAR, Triage, etc.) were given group ID numbers. Tactical teams within each group were also given individual ID numbers to allow the researchers to distinguish among them. Each set of questionnaires was printed with a unique ID number that was used as an on-scene ID for the first responder (FR) who provided information. See a copy of the complete questionnaire packet in Appendix 4. A data logging area was set up in the research notebook to record start/stop times, group IDs, team IDs and FR IDs. The video camera was white balanced and the GPS timestamp recorded with the video camera time overlaid on the image.

Stage 2: Instrumentation and Pre-tactical Questionnaire

Another researcher was assigned as instrumentation lead. This researcher's job was to instrument the tactical commander, the leaders of selected tactical teams and other selected personnel. The instrumentation lead and the tactical commander discussed the expected schedule for advancing each team into the tactical scene to allow the instrumentation lead to plan the sequencing of instrumentation and videotaping.

While each subject was being instrumented, another researcher was taking preliminary questionnaire data. The researcher wrote the FR ID from the questionnaire on a strip of reflective tape that was placed on the first responder to allow ready identification during the tactical activity.

The instrumentation lead transmitted the audio channel number, group ID, tactical team ID, and FR ID to the data monitor who provided a sound check. The data monitor recorded the time of instrumentation in the research notebook and began recording on a new mixer channel in the Studio One software that was named for the audio channel being utilized.

Figure 25 shows a representative data monitoring setup from the subway exercise at Guardian Centers. When the questionnaire lead was not taking data on instrumented subjects, the researcher collected questionnaire preliminary data from other subjects involved in the tactical scene and tagged them with reflective tape so they could be identified later and matched to their individual preliminary questionnaires.

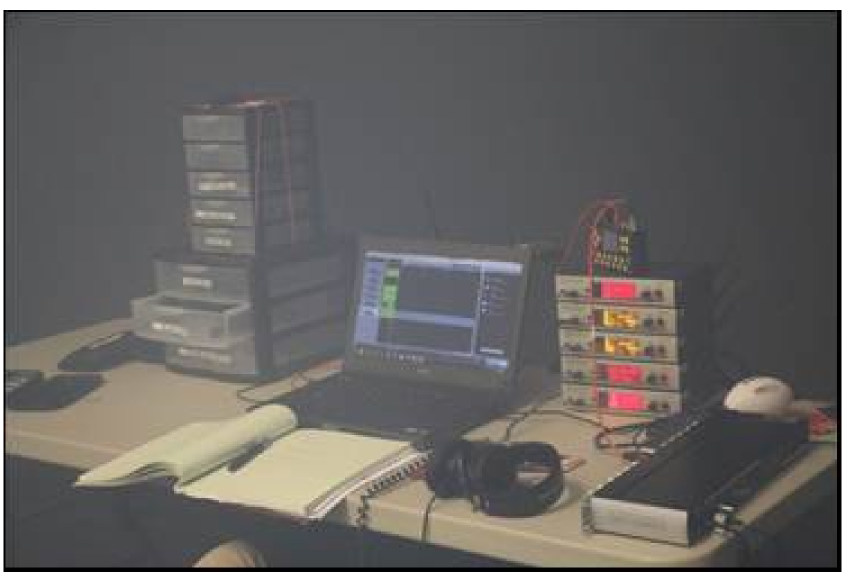

Figure 25. Data Monitoring Workstation at the Subway Exercise

Once all the audio channels were allocated, the instrumentation lead monitored when instrumented teams were staged into the tactical scene. As the teams entered the 'hot zone,' the instrumentation lead transmitted that status to the data monitor who logged the FR ID, recording channel and time in the research notebook. The instrumentation lead recorded video of the instrumented team during their tactical operations.

Stage 3: De-instrumentation and Post-tactical Questionnaire

When tactical teams rotated off of the tactical scene, the instrumentation lead informed the data monitor, who logged the time at which the first responder left the 'hot zone.' The instrumentation lead then removed the instrumentation and transmitted the FR ID and channel to the data monitor, who logged the de-instrumentation time in the research notebook. The questionnaire lead collected post-tactical data at that time as well. The instrument lead then identified other tactical teams scheduled to rotate into the tactical scene and repeated the process described above. The questionnaire lead tracked movement of other personnel into and out of the tactical scene, and collected post-tactical data as soon as possible when they rotated out.

Site Selection, Exercise Details and Site-specific Instrumentation Setup

The researchers selected Guardian Centers (see Figure 26) as a venue for conducting controlled testing and evaluation for two exercises: the initial exercise to validate the research methodology and system checkout, and a large-scale multi-agency and multi-jurisdictional exercise.

Figure 26. An Aerial Photograph of Guardian Centers Located in Perry, Georgia

The researchers also selected two federally directed and supported exercises with a national scope. The first was the U.S. Northern Command (USNORTHCOM) sponsored Vigilant Guard 2015, a multi-jurisdictional, natural disaster response exercise in Georgetown, South Carolina. The second was a Federal Aviation Administration (FAA) mandated mock aircraft crash response conducted at the Hartsfield-Jackson International Airport in Atlanta, Georgia.

The potential risk of RF interference to mission critical communications is a national concern. The researchers determined that the exercises conducted at Guardian Centers, which train emergency response personnel from around the world, the Vigilant Guard exercise, and the mock plane crash at one of the busiest airports in the world, provided the required broadly applicable fidelity for this research.

The annual Georgia Mobile Command Post exercise at Stone Mountain, Georgia was added as a target of opportunity to the list of scenarios. Since this exercise was RF communications-focused, it provided an additional look at RF issues related to statewide interoperability systems. Table 8 shows the research sites used in this study, the participating agencies and the data types they supplied.

Table 8. Summary details of research sites

Scenario	Date	Location	Agencies Participating	Number of Personnel	Data Types	Notes
HRF and CERFP Search and Extraction	9-13 Dec 2014	Guardian Centers	GA Army and AF National Guard	300	RF, HF	Exercise used to validate test approach and equipment
Vigilant Guard	6-9 Mar 2015	Georgetown, SC	Multi-state National Guard, multiple state agencies	2400	RF, HF	Opportunity to gather data during three separate scenarios/ environments
Hartsfield-Atlanta Airport Mock Disaster	15 April 2015	Atlanta, GA	Airport Public Safety, multiple Atlanta area agencies	100	RF	FAA required mass casualty exercise at airport training facility
Mock Subway Attack	28 April 2015	Guardian Centers	Multiple Houston, Bibb, Peach County agencies	50	RF, HF	MERC and GC directed exercise supported by every agency in Middle GA
GEMA MCV Exercise	5 May 2015	Stone Mt, GA	Mobile Command posts from GA	100	RF	Annual statewide mobile command post exercise

RF = Radio Frequency, HF = Human Factors

RESEARCH RESULTS

RF Analytical Framework

RF analysis was performed at multiple levels. As part of the design of each experiment, exercise-specific potential causes of interference were noted and analyzed for likelihood of occurrence. During each experimental exercise, real-time monitoring of known participant frequencies was combined with spectrogram and waterfall analysis techniques to assist in the detection and observance of interference. Following each experiment, the recorded data was post processed. The post processing analysis included digital demodulation analysis and close scrutiny of signal strength and quality.

The analysis performed prior to an exercise included a survey of the known transmitters in the area of the exercise. Frequency information was collected from FCC databases and compared with the public safety frequencies expected during the event. The location and orientation of major power lines near the scene were noted and added to the analysis steps during the operation to observe potential interference contributed by them.

Further, for exercises close in proximity to the researchers' facility, an RF sensor set up on the roof was used to pre-evaluate the digital signal quality of agencies such as the Houston County/Peach County APCO-25 Phase I digital radio system. The researchers used VSA software to demodulate the signal and calculate error rates of the system during normal (non-exercise) operation. The image below is a typical screenshot of VSA while performing digital demodulation analysis.

Figure 27. Digital Demodulation Analysis Performed Using VSA Software

During each exercise, multiple software tools were used. The researcher selected a specific tool based on analysis of which product best matched the spectral data of interest. For example, for quick-look analysis and waterfall representation of the spectrum, Keysight Spectrum Visualizer was used. It was able to access any of the RF sensors and sweep the spectrum, displaying it quickly. This software package is intended to effectively turn the RF Sensor into a simple yet high fidelity spectrum analyzer with easily selected frequency spans and resolution bandwidths.

The workhorse signal analysis tool was the VSA software. The single tool allowed spectrogram analysis, digital demodulation and error-rate calculations, and manipulation of the data using different windowing functions. Figure 28 shows a screenshot from VSA during Vigilant Guard in Georgetown, South Carolina. Markers were placed at each frequency used by the South Carolina Palmetto 800 System for first responders in the area. The upper portion of the image is a real-time capture, showing that two first responders were simultaneously transmitting on separate frequencies (marker 10 and 11).

The lower portion of the image shows a peak-and-hold capture. This type of analysis shows the relative amplitude of transmitters in the area using those frequencies and the usage. Note that markers 8 and 9 show that those two frequencies, although available to the system, were not used during the exercise.

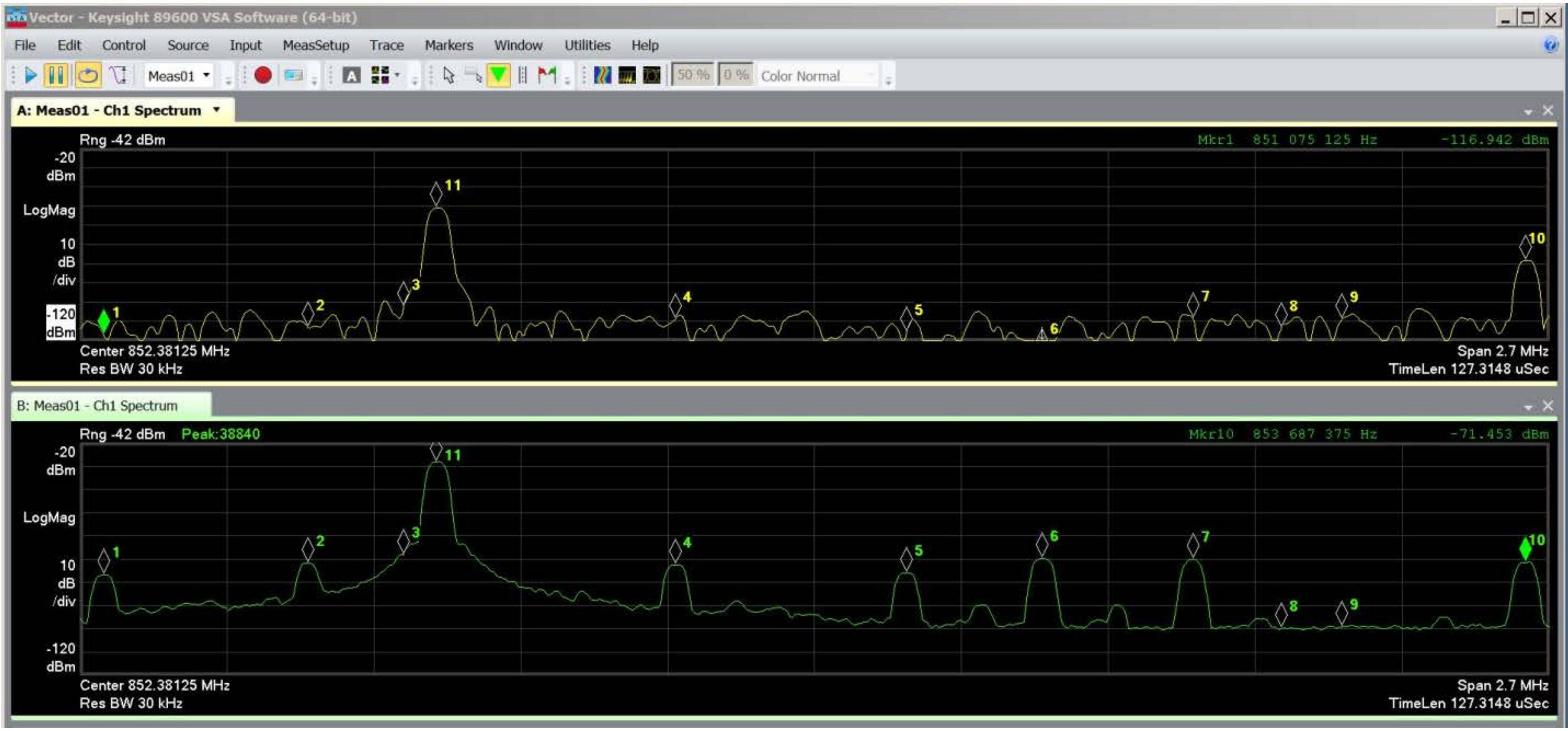

Figure 28. Spectral Data Analysis Performed Using Keysight VSA

The Sensor Management Tool software was used to perform geolocation of transmitters. The image in Figure 29 is a screenshot from the Sensor Management Tool during the December 2014 exercise at Guardian Centers. The information displayed includes the location of the sensors, map of the scene, RF data collected from a transmitter and the calculated geolocation of the transmitter.

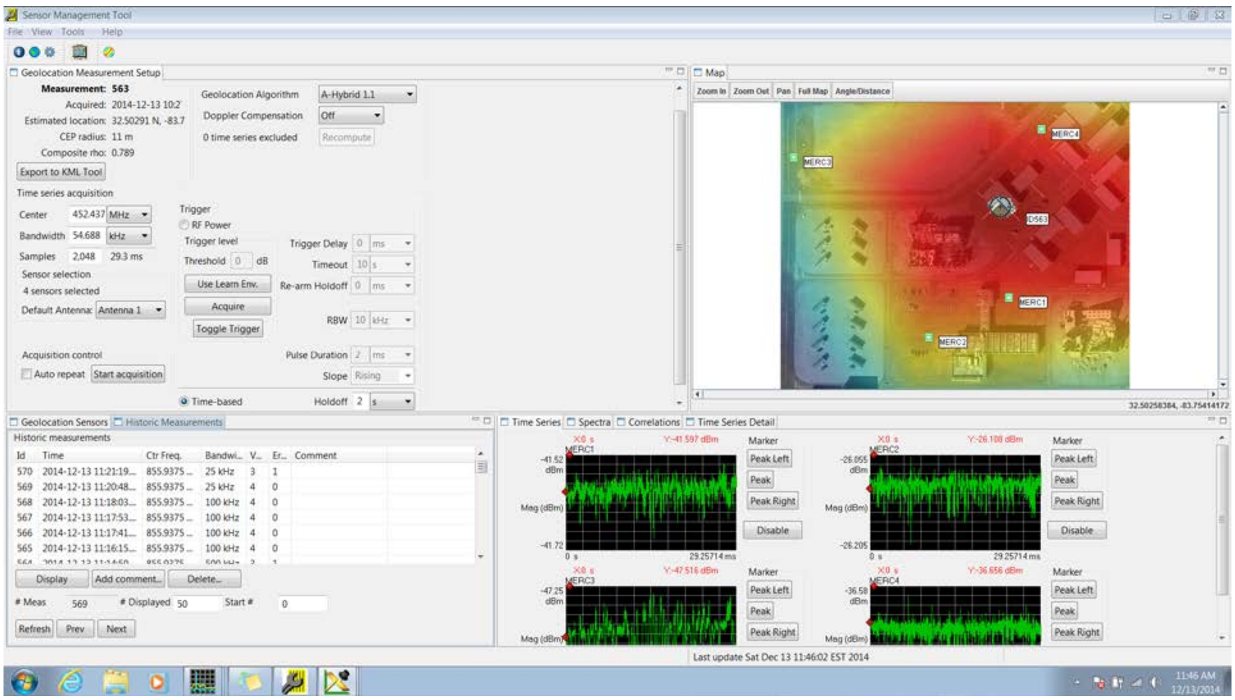

Figure 29. Screenshot from the Sensor Management Tool Showing the Geolocation Capability

Post-exercise analysis included a detailed review of the spectral data collected during the event. Important observations noted during the live event were investigated.   For example, during the HF analysis of audio data collected during an exercise, possible RF interference was discovered that was not observed during the exercise by the RF researchers.   The HF researchers communicated that information to the RF researchers, who analyzed the spectral data collected during that specific timeframe through a correlation analysis.

RF data streams recorded during the exercise were imported into VSA and played on a loop. The resulting display allowed the researchers to see the transmissions as if being collected live, and perform further analyses that were available during the exercise, but not performed due to time constrains or chasing other anomalies from other transmitters.

Wireless Device Typology

The numbers and types of wireless devices used by first responders varied in each exercise, though there were some consistencies. Every scenario involved an 800 MHz digital radio system, though not all of these were trunked. Interoperability gateways, typically ACU 1000 or ACU 5000, were used to provide inter-agency communication methods where needed. Analog radios were used in some cases.

More than 92% of first responders carried hand-held radios, with the remainder being incident commanders or other stationary radio users. The median number of wireless devices carried by first responders was two, but this ranged from one to five devices. Recall that the maximum number of devices was expected to be four. The most commonly carried device, other than hand-held radios, was a cellular smart phone (78.5%). Table 9 shows the distribution of the most commonly available devices for the Vigilant Guard exercise (VG15) and the Subway Explosion exercise (GC15).

Appendix 7 contains tables listing all of the agencies and the wireless equipment each brought to the scenario. The frequency plans for each exercise are also included to illustrate the extent of the wireless communications environment. The radio frequency environments in each exercise were well-planned from a communications perspective, but also very complex at all scales, from the personal area network to the regional level.

Table 9. Wireless Devices Carried By First Responders

Exercise	# of HF Subjects	Median # of Devices	Hand-held (Trunked)	Hand-held (Other)	Smart Phone	Pager	Wireless Personal Alert Safety System (PASS)	Wireless Thermal Imager	GPS Device	CBRNE Sensor	EMS Telemetry	Other
VG15	20	2	18	0	16	8	3	0	0	0	0	1
GC15	45	2	14	28	35	0	1	5	7	1	6	3

VG15 = Vigilant Guard 2015, GC15 = Guardian Centers Subway Explosion 2015

HF Analytical Framework

Random selection and assignment of first responders into specific groups for HF data collection and analysis was not feasible for two main reasons. First, all but one of the exercises were pre-planned far in advance of this study. Although the researchers received excellent support from the participating agencies, it was incumbent upon the researchers to not interfere with the overall training objectives during the exercise. In addition, there were limited numbers of tactical teams at each exercise, even with the extensive overall number of participants. For these reasons, the participants were purposefully selected for participation in the study.

The researchers worked with the incident commanders at each scenario to identify which teams were performing complex, time-sensitive, and both mentally and physically demanding tasks. Examples of tasks selected for this study are search and extraction (S&E), triage and rescue operations (RO). At the time that the teams of interest (TOI) were selected, the commander assigned a specific squad leader to wear the audio instrumentation.

This was done to mitigate the potential for researcher selection bias in subject selection. The analytical outcomes can be tested for validity and selection bias, using data from the human factors questionnaires drawn from other tactical teams.

The incident commander was instrumented in order to collect audio from both endpoints of the communications link. This was crucial for allowing the researchers to identify when communications were lost and why. It also provided a broader measure of radio traffic through the Incident Commander and a qualitative assessment of situational awareness and control by the commander. Other individuals participating in the scenario were instrumented as well, so that there were multiple audio feeds. The multiple feeds were used to discriminate among different types of communications issues.

Demographic data was collected on all of the instrumented participants and the majority of the other first responders in the scenario. Data was collected on a total of 81 participants. Six were female, one of whom was chosen for audio instrumentation.

Table 10 shows the demographic distribution of participants.

Table 10. Participant Demographic Data Distribution from the Subway Exercise

Years of Experience	EMA	EMS	Fire	National Guard	Police
<2	0	0	6	6	3

Years of Experience	EMA	EMS	Fire	National Guard	Police
2-5	0	2	6	8	2
6-10	2	0	0	4	3
>10	0	8	16	1	11
Total	2	10	28	19	19

EMA=emergency management agency;
EMS=emergency medical service (ambulance, medical transport).

Questionnaire data and exercise data were entered in a Microsoft Access database so the data could be queried and exported into tables and reports as needed. A diagram of the database table structures can be seen in Appendix 5.

Audio data was manually extracted from each recorded audio channel. Data collection for tactical teams was started at the timestamp corresponding to the time the team entered the 'hot zone' and was stopped when the teams exited the 'hot zone.' The start and stop times for each data collection range were entered in a data collection spreadsheet. (See Appendix 6 for a representative data collection spreadsheet from the Vigilant Guard exercise.)

Teams that entered the tactical scene multiple times had a separate data collection range for each occasion. A separate data collection range was also created if an audio feed was lost or made incomprehensible by problems with the Sennheiser radio signal. This allowed the researchers to calculate a percentage of the total recording from which data could be collected, and to determine whether the data lost significant validity due to the data losses.

All verbal exchanges with the team leader and all radio traffic between the team leader and other units (primarily the tactical commander, but sometimes other team leaders) were logged in the data collection spreadsheet. Each exchange was categorized with regard to the modality of communication (direct or radio) and the type of communication involved. The radio communications were classified into the following types:

- Call Request – involves stating who is calling and for whom.
- Call Acknowledgement – indicates understanding and/or compliance, usually including repetition of the command or transmitted information.
- Command – direction or request for action.

- Correction – identifies incorrect information (error of commission) was acknowledged by the receiving party.
- New Information.
- Requesting Repeat – did not understand the information transmitted (psychoacoustic or inattention error).
- Requesting Information.
- Responding to Information Request.
- Status Request.
- Status Response – providing information on team status in response to status request.

Each radio exchange was marked in the audio recording software with the marker number and time logged in the data collection spreadsheet. Notes on problematic transmissions, such as repetitions due to ignored or lost transmissions, were logged with the transmission logs as they occurred.

Verbal exchanges with the tactical team leader were classified in a similar manner to radio transmissions with two exceptions: Call Requests were classified as Attention Requests (e.g., "Hey Sergeant Jones!") and Call Acknowledgements were classified as Attention Acknowledgements (e.g., "I heard what you said."). An additional category of miscellaneous verbalizations was included to capture banter and other non-tactically directed communications among team personnel.

The wide variability among individuals in verbal expression as well as differences in information content between communication modalities was a significant concern when planning the means to measure the amount of information transmitted verbally, by radio, and by gestures or signals. The data was normalized by weighting each data point by a categorical value representing the minimum amount of information that can be transmitted.

For example, the minimum verbal data exchange (radio or interpersonal) requires three (3) words, even if one or more are tacitly understood; subject, verb and object. Gestures and signals like alarms or flashing lights involve only a verb (e.g., ‘stop,’ ‘listen,’ ‘look’). The researchers therefore assigned a value of 6 bytes to each verbal data exchange and 2 bytes to every gestural or signal exchange. These values were based on the 2 bytes required to represent a word in a computational data stream.

This technique dramatically underestimates the total amount of data transmitted verbally in most normal exchanges, as discussed above. However, the normalization allows for a comparison between subjects who are terse versus those who are wordy. It also allows for a comparison between those who use good radio operating procedures versus those who speak with their team members more expansively during tactical exchanges.

Additionally, normalization enabled the use of a simplified method for calculating the error rates common to both interpersonal and radio transmissions. The following were counted as transmission errors:

- Corrections (n_c) – Each transmission used to correct the receiving party counts as 6 bytes of error.
- Ignored/Lost (n_L) – Each repeated transmission assumes delayed, ignored or lost information from a previous transmission and counts as 6 bytes of error. Multiple repetitions of the same transmission count as separate errors, since the increasing delay represents increasing loss of information.
- Request Repetition (n_r) – Each request for repetition of a previous transmission counts as 6 bytes of error.

Information loss (L) could thus be expressed as a ratio of the error information to the total amount of information (minus the correction and the requests for repetition, which would otherwise be duplicative). The formula below can be calculated for both radio-mediated losses and total information loss.

$$L = 6\frac{(n_c + n_L + n_r)}{(n_T - n_c - n_r)}$$

The National Incident Management System Incident Complexity Scale

Each of the exercises provided opportunities to collect data from realistic, large-scale, multi-agency scenarios involving extensive numbers and types of first responders. The National Incident Management System (NIMS) incident complexity scale provides a means for comparing different scenarios for the level of resources and expertise required to handle them. A copy of the NIMS incident type classification can be found in Appendix 1. Using this scheme, each of the scenarios were classified as shown in Table 11.

Table 11. Listing of Data Collection Events with Personnel and NIMS Type

Exercise	Agency Types (local, regional, national)	Total Number of Personnel	Number of HF Subjects	Average Experience (yrs)	NIMS Type
GC14	Local, regional, national	300	13	4	2
VG15	Local, regional, national	2400	20	9	1
Hartsfield	Local, regional	100	--	--	3
GC15	Local, regional	50	48	15	4
GEMA MCV	Local, regional	100	--	--	4

GC14 = Guardian Centers 2014, VG15 = Vigilant Guard 2015, GC15 = Guardian Centers Subway Explosion 2015, GEMA MCV = Georgia Emergency Management Mobile Communications

Expertise Categorization

The types of roles assumed by the participants from whom we collected data included: incident command, technical set up, communication management, medical transport, triage, policing, hazardous materials assessment, explosives management, reconnaissance, engineering (i.e., breeching, shoring, etc.), and search and extraction. They had an average of 12 years of experience as first responders, ranging from less than one year to 38 years.

As part of the data collection, each responder was asked at the start to rate his/her expertise in performing their assigned roles in the exercise. The choices were novice, competent or proficient. The majority (82.7%) rated themselves as competent or proficient in their roles. Table 12 shows the distribution of first responders in each exercise scenario.

Table 12. Distribution of Exercise Participants by Exercise and Their Self-Rated Expertise

Exercise	Subjects	Average Years of Experience	Novice	Competent	Proficient
GC14	13	4	2	9	2
VG15	20	9	6	8	6

Exercise	Subjects	Average Years of Experience	Novice	Competent	Proficient
GC15	48	15	6	31	11
All	81	12	14	48	19

GC14 = Guardian Centers 2014, VG15 = Vigilant Guard 2015, GC15 = Guardian Centers Subway Explosion 2015

A more detailed breakdown of participants by range of experience shows a relatively even distribution of numbers in each range. The picture of self-reported expertise was much more complex within these ranges; however, with some subjects having less than two years of experience rating themselves competent and others having more than 20 years of experience rating themselves as novices.

This variability may reflect differences in the frequency and range of training available for responders in different types of organizations. For instance, responders in National Guard units train across a broader range of roles and scenarios than those in rural sheriffs' departments or fire departments. Table 13 shows the distribution of first responders by experience range and agency.

Table 13. Distribution of Participants by Range of Experience, Expertise and Agency

Exp. Range	Subjects	N	C	P	Fire	Guard	Police	EMS	Other
<2	14	5	9	0	6	5	3	0	0
2-5	18	1	13	4	6	8	2	2	0
6-10	12	3	5	4	3	4	4	0	1
11-20	21	3	12	6	10	1	5	5	0
>20	16	2	9	5	6	0	6	3	1
Total	81								

Key: N = Novice; C = Competent; P = Proficient

Georgia National Guard Search and Extraction Exercise (GC-14)

The first data collection event was GC-14, a Georgia Army and Air National Guard Homeland Response Force (HRF) Search and Extraction exercise at Guardian Centers in Perry, Georgia from December 9-13 2014 (Figure 30). The purpose of this exercise was to validate the research data collection systems and protocols the researchers had designed. The scenario involved an explosion and building collapse. Potential hazardous chemical exposure compounded the search and rescue operation.

Figure 30. Georgia National Guard HRF and CERF-P Staging Area at Guardian Centers

After extinguishing fires, the local fire department command requested assistance from the HRF and their subordinate Chemical, Biological, Radiological and Nuclear (CBRNE) Enhanced Response Force Package (CERF-P). The CERF-P is used to support search and extraction, technical rescue and other rescue operations within a hazardous environment. CERF-P teams geared up in full personal protective equipment (PPE), as shown in Figure 31, due to the notional threat of unknown chemicals present in the atmosphere.

Figure 31. CBRNE Personnel Suit Up in PPE for a Hazardous Chemical Environment

The GC-14 exercise parameters were:

- Number of participants:
    - 300 Georgia (Army and Air) National Guard personnel.

- 10 local first responders (fire, EMS, police).
- Average PAN count was two devices per person (however, additional devices were added to the environment to increase the total number of devices.

- Equipment used by participants:
    - Motorola XTS5000 and XTS1500 portable radios.
    - Department and personal cell phones.
    - News media cameras and wireless microphones.
    - InMotion computer systems.
    - Globe Manufacturing Company Wearable Advanced Sensor Platform (WASP).
    - VHF state band mobile radios.
    - Broad area Wi-Fi established by Georgia Air National Guard.
    - Bluetooth hands-free devices.
    - Satellite link up.
    - CBRNE sensing equipment.
    - Personal Protective Equipment.
- The EMS ambulance communications gear included:
    - 800 MHz radio system which serves as their primary dispatch radio.
    - 400 MHz radio.
    - InMotion on-board computer system with a 4G card and GPS system to track all available ambulances.
    - Mobile Data Terminal (MDT) used to text the 911 Center.
    - Toughbook laptop for patient care reports.

- VHF radio on a state-wide frequency band used to communicate with any hospital while en route.
- VHF mobile radio specifically to communicate with Robins Air Force Base Fire and Police Departments.
- EMS personnel also had their personal cell phones and a Nook reader.

The Perry Fire Department used the Motorola XTS-1500, a department-issued cell phone, their personal cell phones and SCBA. The Perry Police Department used the Motorola XTS-5000, a department-issued iPhone 5 and Motorola Astro in-car camera.

The Guardian Centers digital UHF trunked system was used due to the smaller size of the tactical teams and ease of deployment. The FCC licensed system, WQRX491, operates in the range of 451 to 469 MHz.

The researchers examined National Guard and first responder communications interoperability during this exercise as a target of opportunity. As the lead headquarters element, the HRF communications staff typically establishes communications with on-scene emergency response personnel and then maintains continuous communications with them until the emergency operation is complete. However, the HRF exercises are normally focused on military personnel, and first responder collaboration is typically notional and rarely incorporated into their training. Prior to the start of the exercise, the researchers provided all local first responders received with an overview of the exercise scenario and the training. The first responders then met with the HRF communications staff to discuss how their systems would interface with the Joint Incident Site Communication Capability (JISCC) via the ACU-5000 interoperability gateway.

The ACU-5000 provides a hardware interface for compatibility between different radio systems. The unit requires a single handheld radio of each type and a patch cable to the system in order to function properly for radios not already in the system. A weakness of this system is the great diversity of available radio systems and unique patch cables required for interoperability.

The ACU-5000 is used sparingly and, therefore, operational training and maintenance of the system are limiting factors. The researchers coordinated with the Houston County 911 Call Center Communications Officer to join the exercise in order to provide additional technical support to establish communications interoperability. The HRF was able to establish communications with the local fire department using the ACU-5000.

The RF environment was also populated with signals from the local news station and equipment from the National Guard Public Affairs Office. Additionally, Globe Manufacturing Company, LLC supported the exercise by providing Wearable Advanced Sensor Platform (WASP) systems, a specially designed t-shirt that incorporates physiological monitoring technology and a belt for tracking personnel in three dimensions.

The researchers positioned four RF sensor tripods and a master control tripod around the perimeter of the exercise area, a collapsed three story building that was used to conduct search and extraction training. A handheld Fieldfox spectrum analyzer was also used to supplement the sensor towers for data verification and quick observations.

The researchers outfitted each of the S&E teams with wireless microphones and videotaped their activities to determine the impacts of mental and physical fatigue, ambient noise and RF signal degradation on the first responders' ability to effectively communicate and accomplish their mission. The researchers also formally surveyed the participants. The survey results are used in the analysis of the time stamped audio and video data collected.

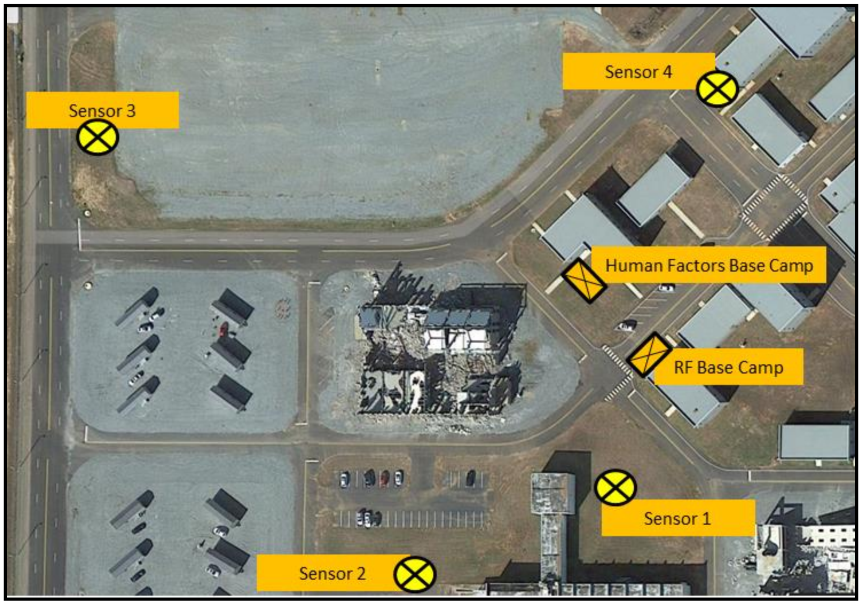

Figure 32. Location of the RF and HF Data Collection Systems. (Photo courtesy of Google Earth)

Figure 33 shows one of the collapsed buildings from which role players were extracted by the CERF-P, with support from the Federal Emergency Management Agency (FEMA) Region IV Homeland Response Force (HRF).

Figure 33. National Guard Soldiers Evacuate Role Players from Chemical Threat Environment

GC-14 RF Analysis

The researchers did not expect to witness substantial interference at the event due to the detailed frequency allocation plan established during exercise planning. The researchers did observe RF interference between media agencies that had not coordinated video/audio wireless equipment ahead of time. However, RF transmissions of first responders were clean. Detailed spectral images were collected that verify the reports of clear communications at the event.

As shown in Figure 34, the Keysight FieldFox spectrum analyzer was used with a broadband discone antenna to collect data around the operating frequencies.

Figure 34. Keysight Fieldfox and Broadband Discone Antenna Used for Data Collection

MERC observed a benign RF environment with clear communications reported throughout the event. Well-planned frequencies distributed across the band resulted in no interference issues. The waterfall plot shown in Figure 35 was collected over a span of several minutes during rescue operations. The peak on the left is the trunked system control channel. The peak on the right is the periodic transmission of voice audio.

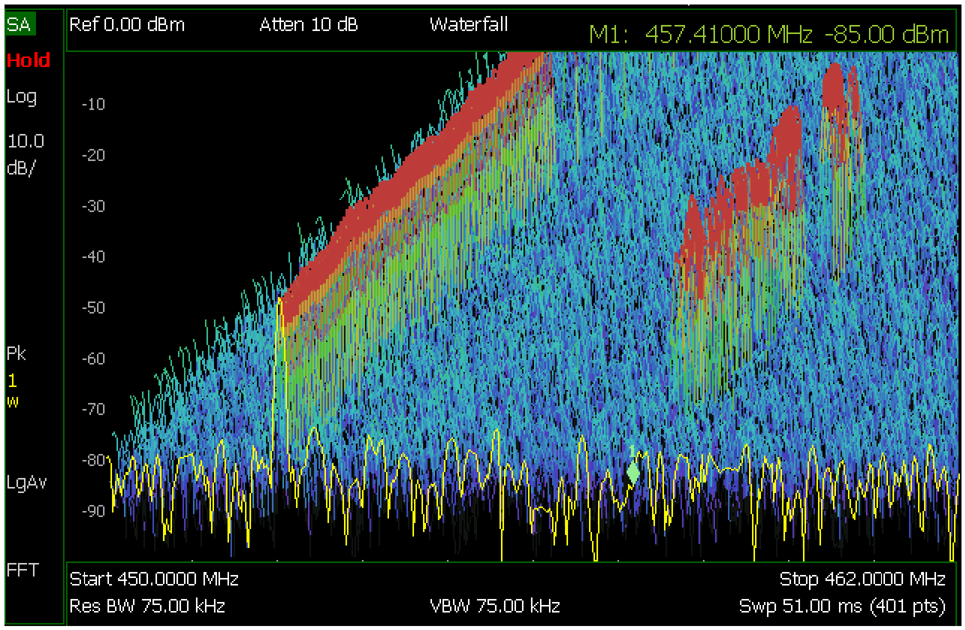

Figure 35. Waterfall Analysis of Guardian Centers Radio System Traffic

Figure 36 shows the transmission of an emerging PAN technology, the WASP body worn sensor data. The upper panel shows the strong carrier frequency of the WASP transmitter at 154 MHz. No significant signals were present in the vicinity of the carrier, resulting in no interference issues. The lower panel is a spectrogram showing the burst mode of the WASP transmitter. No signs of interference were detected in this analysis.

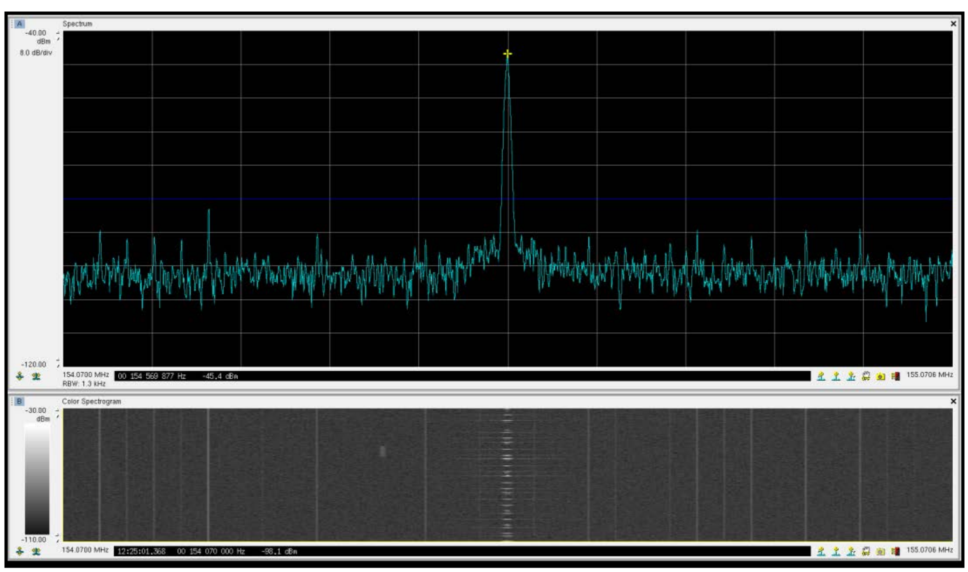

Figure 36. Spectral Data Collected from Emerging WASP Body Worn Sensor Equipment

Figure 37 shows typical spectral data during radio transmissions from the CBRNE teams and the Search and Extraction teams. This spectrum was captured during simultaneous transmissions from both teams. Strong carrier frequencies (military frequencies 396.925 and 397.125 MHz) with adequate separation demonstrated minimal chance of interference.

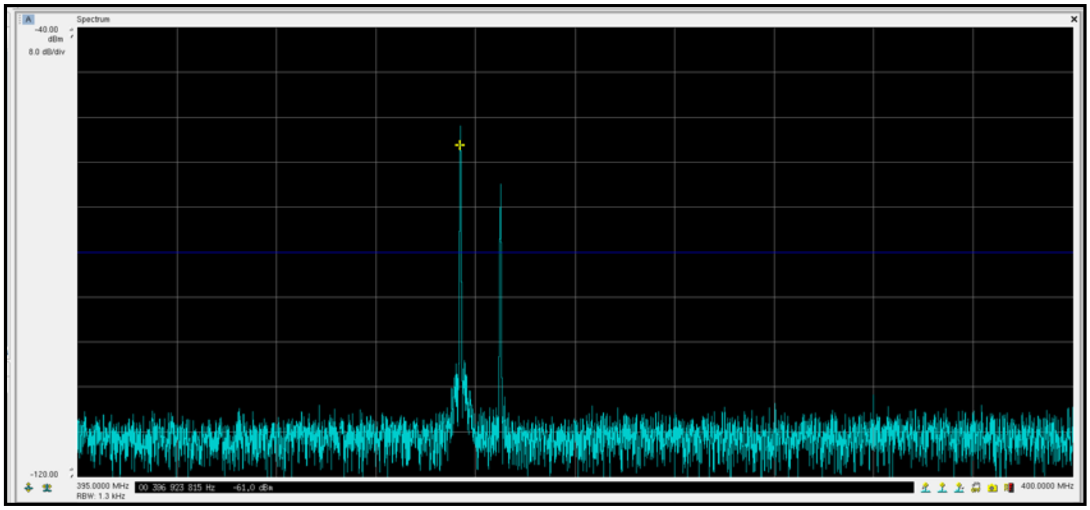

Figure 37. National Guard Radio Traffic

Overall safety and command and control of the exercise scenario were carried out using GC's UHF digital trunked radio system. The FCC licensed system, WQRX491, operates in the range of 451 to 469 MHz. Clear carrier frequencies were noted within the system with no spurious or unaccounted-for spectral energy, as shown in Figure 38.

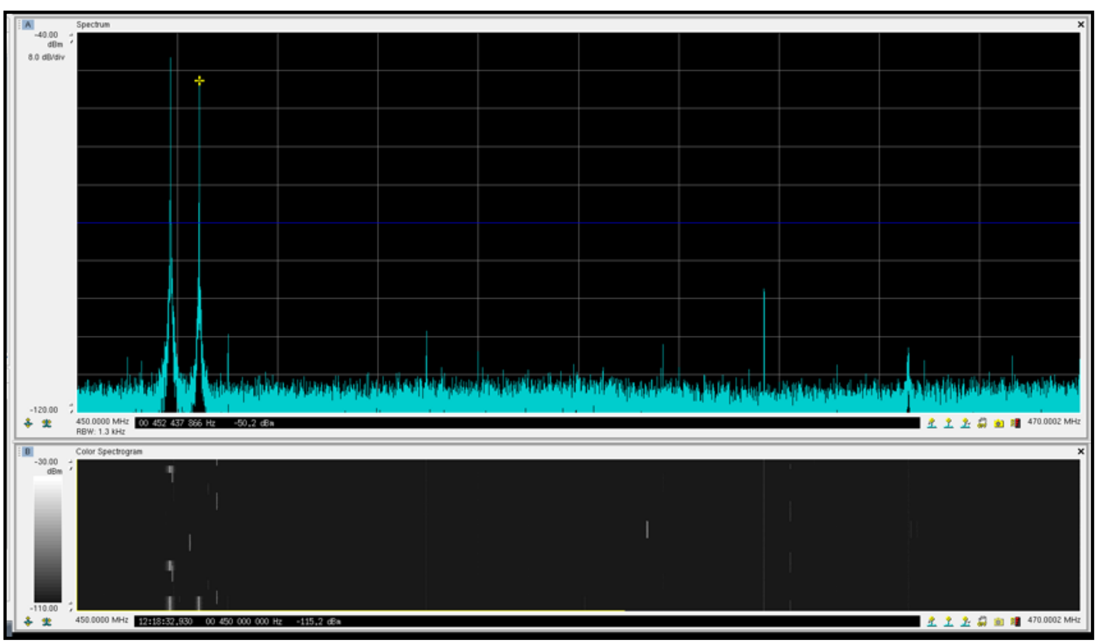

Figure 38. Spectral Data from Guardian Centers Exercise Control Radios

Local firefighters, paramedics and law enforcement personnel used the Houston County P25 digital trunked 800MHz system. The spectral data shown in Figure 39 below demonstrates excellent channel separation on the system and a very low noise floor. The spectrogram in the bottom pane shows the relative usage of each of the channels with no signs of interference.

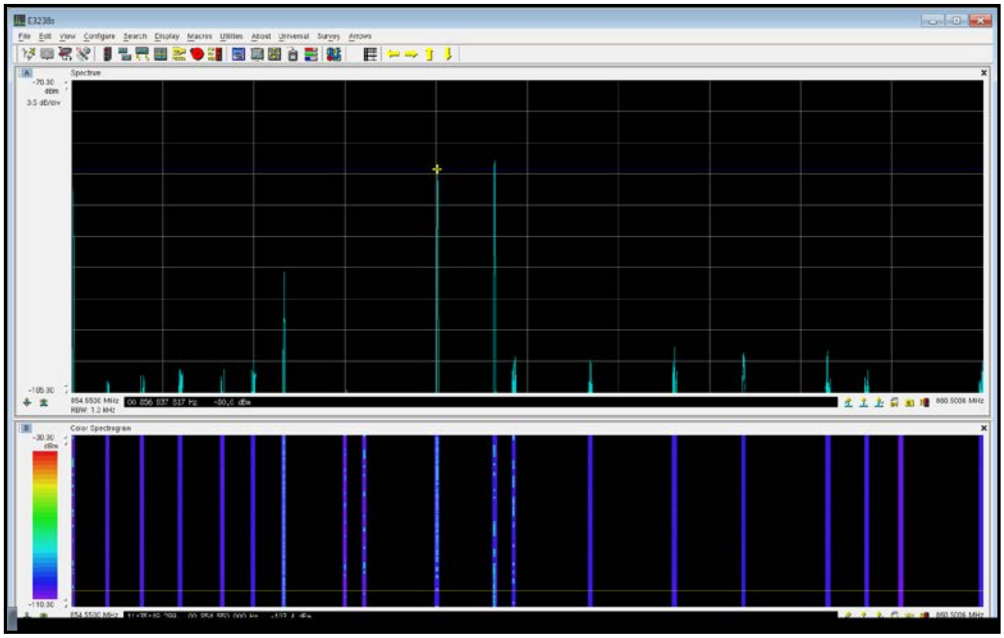

Figure 39. P25 Digital Trunked 800mhz System Channel Separation

A demodulation analysis was performed on the Houston County digital radio system to look for signs of data transfer collisions and interference. As shown in Figure 40, the overall digital error rate was calculated to be 1.5%. This error rate signifies no issues with interference within the digital system.

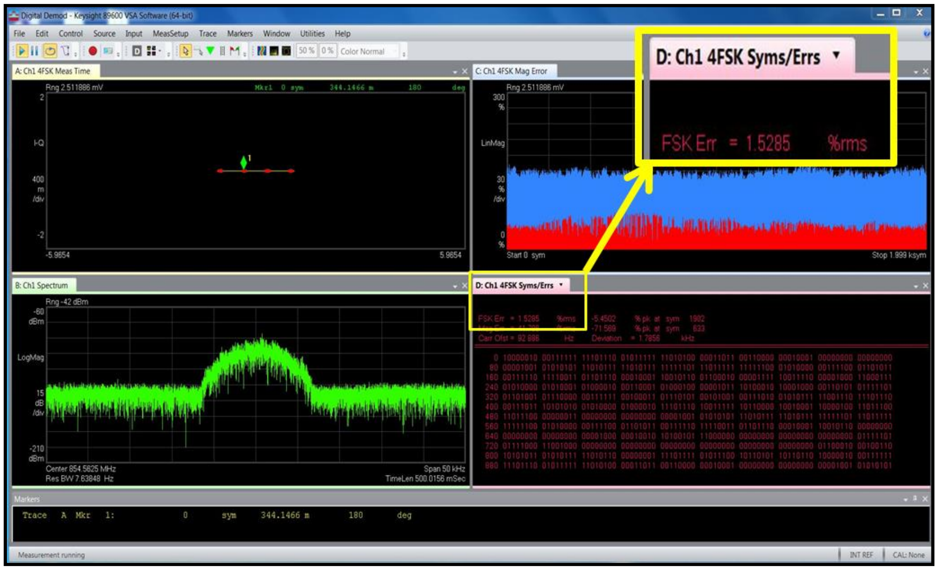

Figure 40. Digital Demodulation Analysis of the Houston County Radio System

A Wi-Fi network was established by the National Guard to be used during the exercise. Although Wi-Fi was not used for first responder activities, it was used for ancillary activities such as reporting results and email exchange between local commanders and headquarters offsite. The 2.4 GHz band was evaluated for signs of interfering energy. In Figure 41 below, the collected spectral data is shown, including a spectrogram in the lower panel. No interference was noted as the band spread appeared typical for Wi-Fi.

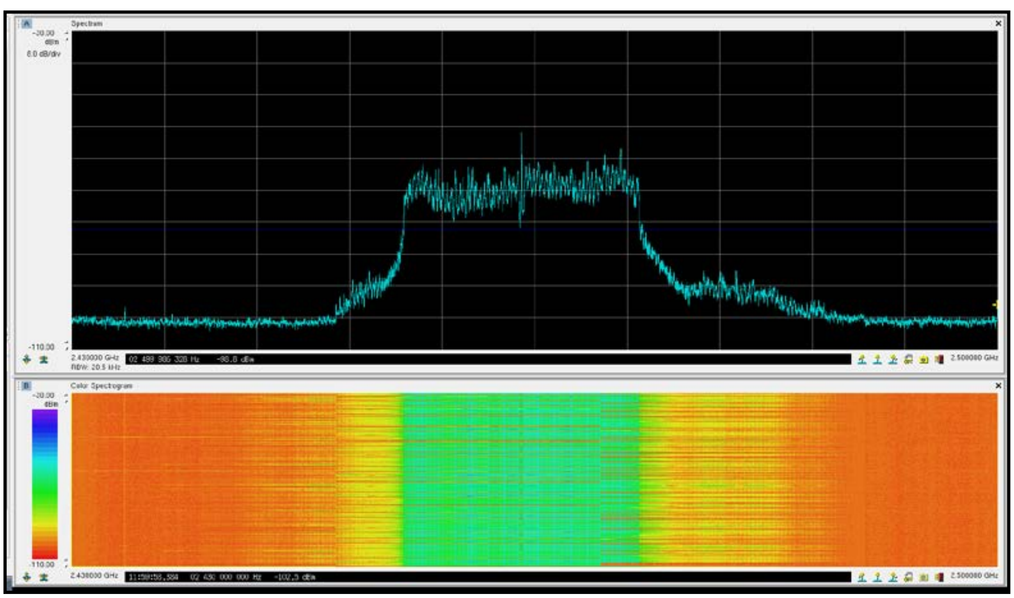

Figure 41. Wi-fi Spectral Analysis

The researchers evaluated the passive geolocation capabilities of the software and hardware as an emerging technology, which can be used to track first responders using their

PAN RF signatures. The Keysight system uses relative amplitude and time difference of arrival (TDOA) of signals received at each antenna location to determine the location of a radio source. The geolocation algorithms of the Keysight equipment successfully located transmitters in the scene as shown in Figure 42. To validate the geolocation capabilities of the system, the researchers placed a transmitter of known frequency and location in the environment and successfully geolocated it using the system.

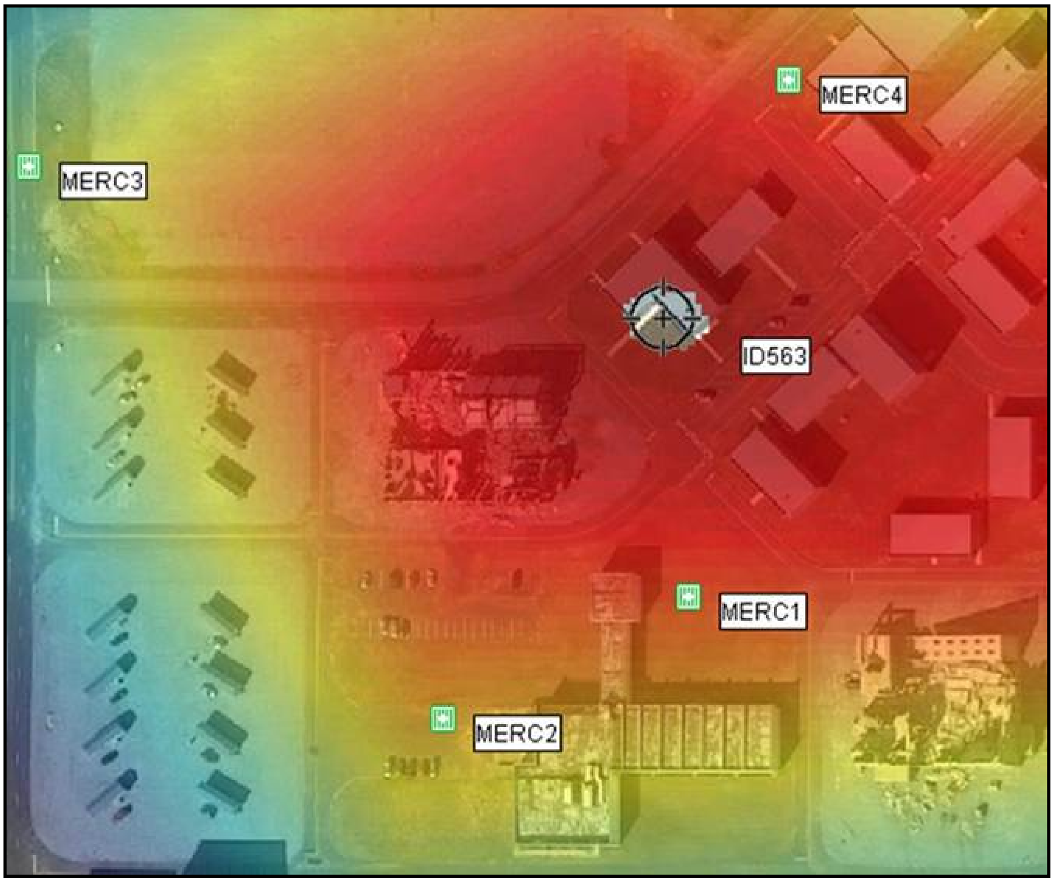

Figure 42. Passive Geolocation of a Known Transmitter Using the Transmitted Signal

GC-14 HF Analysis

Audio data from one responder team in the CERF-P exercise (shoring team) at Guardian Centers (GC-14) showed that 14.9% of the information transmitted by radio was lost due to some type of signal loss or signal degradation. The audio data collected from the tactical command and other tactical teams in this exercise was severely limited by signal loss or interference on the Sennheiser units and proved unusable.

Therefore, the researchers were not able to discriminate among causes of loss for this exercise, nor compare the shoring team data to other teams. However, the lack of any detected RF power or frequency effects by the RF researchers indicates the signal problems were most probably related to ambient noise interference, auditory pathway interference and loss of auditory attention (inattentional blindness). Table 14 shows the radio and interpersonal information transfer and error rates from GC-14.

Table 14. Cumulative Information Transfer and Errors for both Radio and Interpersonal Transmissions

RADIO TRAFFIC		VERBAL TRAFFIC	
0	INCORRECT	**0**	INCORRECT
3	IGNORED	**0**	IGNORED
8	REQUEST REPEAT	**5**	REQUEST REPEAT
82	TOTAL XMIT	**334**	TOTAL XMIT
19.7%	%Total Comms	**80.3%**	%Total Comms
14.9%	RADIO INFO LOSS	**1.5%**	INTERPERSONAL INFO LOSS

The participants' ratings of the overall quality of radio communications were of interest in this research. Both the shoring team leader, who wore SCBA during the audio recording period, and the tactical commander rated overall communication as good (second best rating) with no noted communication interference, notwithstanding the significant loss of information measured through the audio recordings.

The SCBA, coupled with ambient noise (primarily hammering and voices), had a dramatic effect on radio traffic intelligibility in both directions. Figure 43 and Figure 44 show a comparison of clear audio frequency spectra from the team leader and the tactical commander.

The team leader received an unimpaired voice signal (400 Hz to 1.5 kHz) from the radio, with no interference at lower or higher speech frequencies, even through the SCBA. The clear audio received by the tactical commander showed frequency shifting toward the lower frequencies, with competing audio below 400 Hz. This is consistent with the muffling effect of speaking through SCBA. Although it was intelligible, the quality was impaired even without any transmitted noise influence.

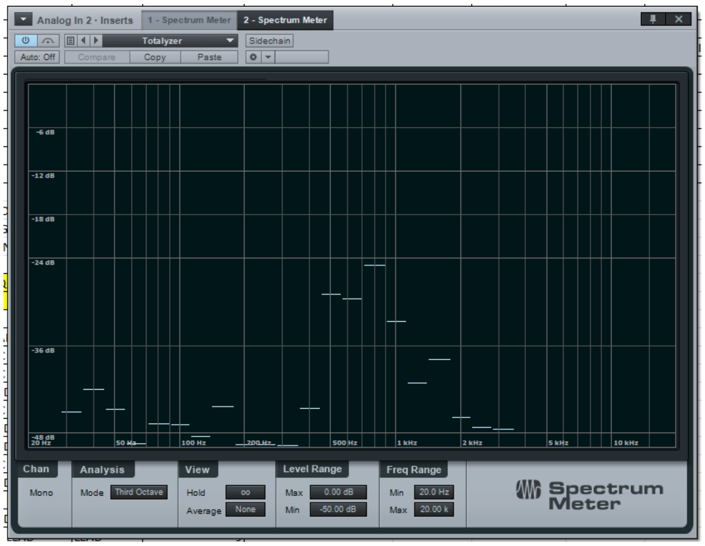

Figure 43. Spectrogram of Clear Audio Received by the Team Leader

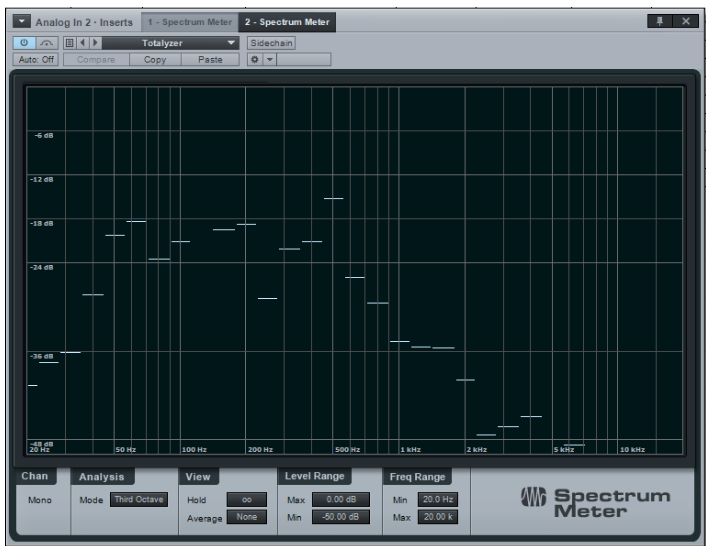

Figure 44. Spectrogram of Clear Audio received by the Tactical Commander

Note the shift of the peak power frequency from 800 Hz received by the team leader to 500 Hz received by the tactical commander.

The addition of ambient and transmitted noise significantly reduced the intelligibility. Figure 45 and Figure 46 show a spectrogram of the unintelligible transmitted speech for both the team leader and the tactical commander. Both graphs exhibit elevation of the noise floor across all frequencies from 20 Hz to 3.5 kHz, which masks the entire range of speech frequencies.

Figure 45. Spectrogram of Garbled Audio Received by the Team Leader

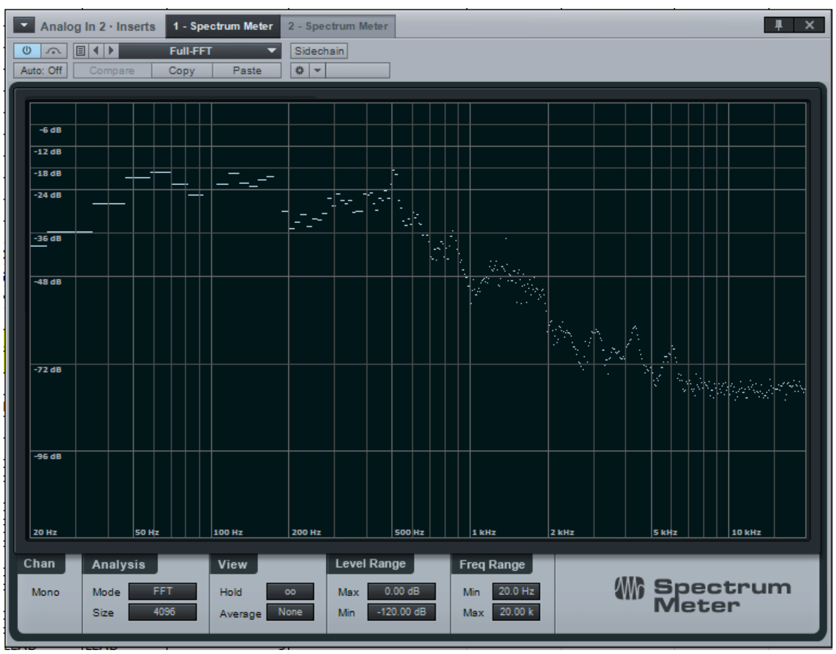

Figure 46. Spectrograms of Garbled Audio Received by the Tactical Commander

Vigilant Guard 2015 (VG-15)

The Vigilant Guard Exercise program is sponsored by U.S. Northern Command (USNORTHCOM) in conjunction with the National Guard Bureau (NGB), and provides the opportunity for states to improve cooperation and relationships with their regional civilian, military and federal partners in preparation for emergencies and catastrophic events.

More than 2,400 personnel from South Carolina, Florida, Georgia, North Carolina, and Virginia responded to numerous disaster scenarios throughout South Carolina during the exercise held March 6-9, 2015. Georgetown, South Carolina was the focal point for some of the largest events, and included: a collapsed building at the Choppee Regional Complex; a collapsed bridge that previously connected Georgetown with Pawley Island; a notional nursing home evacuation following a tornado (at the Eagle Electric Complex); and large-scale medevac operations at the Georgetown Airport.

The VG-15 exercise showed much more significant and complex patterns of signal loss and signal degradation than the GC-14 exercise. Of the four primary scenarios used for the exercise, two had measureable levels of RF signal disruption or degradation. These were the Georgetown Regional Airport, where medical support and regional communications were based, and at the nursing home tornado response site located at the Eagle Electric Complex.

Scenario 1: South Carolina Helicopter Aquatic Rescue Team Operation

The researchers monitored the recovery of dozens of victims stranded on a broken bridge across the Great Pee Dee River. The primary training participants were the South Carolina Helicopter Aquatic Rescue Team (SC-HART) and two South Carolina Army National Guard (SC ARNG) UH-60 aircrews. SC-HART is a collaborative effort between the State Urban Search and Rescue Task Force (SC-TF1) and the Army National Guard Aviation Unit from McEntire Joint National Guard Base (JNGB).

Four fire department boats from Georgetown and Midway Fire Departments and the U.S. Coast Guard also participated. South Carolina Highway Patrol positioned two vehicles on the primary bridge to keep civilian traffic flowing. Approximately 45 SC ARNG soldiers, serving as stranded victim role players, were hoisted individually into the helicopters by the SC-HART team.

The researchers collected RF data throughout the training event. The HF researchers did not have the opportunity to collect data during the bridge scenario due to the nature of this limited air operation.

Table 15 shows a matrix of the PAN devices in use at the exercise. They include:

- SC-HART primary equipment included the Palmetto 800 Mobile Land Radio (MLR). They also use a Bluetooth enabled GoPro Camera. The aquatic team only used the wireless GoPro camera. They used no voice communication devices. They relied on hand and arm signals to communicate with their team member in the UH-60.
- The fire rescue boats communication devices included ICOM VHF Marine IC M-504 radios, cell phones, Garmin GPS, GoPro and sonar navigation.
- The SC ARNG used the Palmetto 800 and cell phones.

Table 15. PAN Device Matrix of VG-15 Participants

Agency	# Prsns	Mobile Radio	Cell Phone	Pager	PASS	IR Imager	GPS	Robots	CBRNE Sensors	RFID	EMS Telemetry	GoPro	Phys. Monitor	Patient Monitoring
GTFD	45	APX 6000	X	VHF	SIM II	ISG/ Infrasys	On Engines		X	Other: Wireless remote deck gun; 4G Hotspot; voice amplifier				
GT EMS	8	APX 6000	X				X				X			X
Midway Fire Rescue Boat	8	X	X				Garmin					GoPro		
SC-HART	30	X	X									GoPro		
GT FD IC	1	X	X			ISG/ Infrasys	Other: Verizon jetpack hotspot; sigtronics ultra sound wireless headphones; Dell computer/monitor							
GT Sheriff	4	X	X											
SC AND FD	20	X	X											
SC State Def. Force	45	X	X											
Red Cross	2		X				X	Other: PA System						
JISCC	8	X	X	Other: SATCO: VHF/UHF/800 Mhz; UHF Repeaters; VOIP; VTC; WiFi; ACU-1000										
MED-1	20	X	X										X	X

Scenario 2: Georgetown Fire Department Tornado Response

One of the major sources of data collection was the Georgetown Fire Department (GTFD) response to the notional tornado destruction of a nursing home. The event occurred at the former Eagle Electric complex approximately three miles north of the fire station on Highway 17 and two miles south of the airport, which was used as the mobile medical treatment facility. Twenty-seven (27) role players served as nursing home victims. Many of the role players were language instructors at Ft. Bragg in their professional jobs and they spoke several foreign languages during the rescue operation (see Figure 47).

Approximately 22 firefighters responded to this event. Engine 20 was the first to arrive on scene with three firefighters. Additional fire trucks soon followed, to included Engine 12, Engine 17, Engine 22, Rescue 15 and Hazmat 16, the Special Operations and Support Unit. Other units at the site included about 45 personnel from South Carolina State Defense Force, approximately 20 SC ARNG firefighters with two tactical fire trucks, a Red Cross Disaster Relief van and a Georgetown EMS team that provided real-world site safety.

Figure 47. Georgetown Firemen Assist a Role Player

The researchers pre-positioned four antenna stands around the perimeter of the complex and monitored activity from a vehicle, which was configured with an antenna on the roof and a laptop securely mounted next to the driver's seat that was connected to a Keysight RF spectrum analyzer. The researchers began scanning the RF spectrum as soon as the first responders arrived and continued to collect for the next five hours.

The HF researchers established a monitoring station next to the building that housed the role players. Several fire fighters and National Guardsmen were outfitted with audio monitoring devices in order to capture detailed audio records of communications challenges. The researchers gathered 13 written surveys from exercise participants. The Incident Command Accountability Officer also wore the audio instrumentation.

Tornado Response Scenario Analysis

During the tornado response scenario, the researchers investigated the potential interference caused by gas-powered generators used on the scene. For the test, lower frequency spectra (90-115 MHz) were collected. This band was selected due to a large number of FM radio stations in the area and their fixed output power and relative amplitudes during the experiment.

In the first test case, a high-quality, commercial off-the-shelf inverter-generator was started and loaded at approximately 150 watts. The measured spectrum below shows a flat noise floor between -90 and -100 dBm.

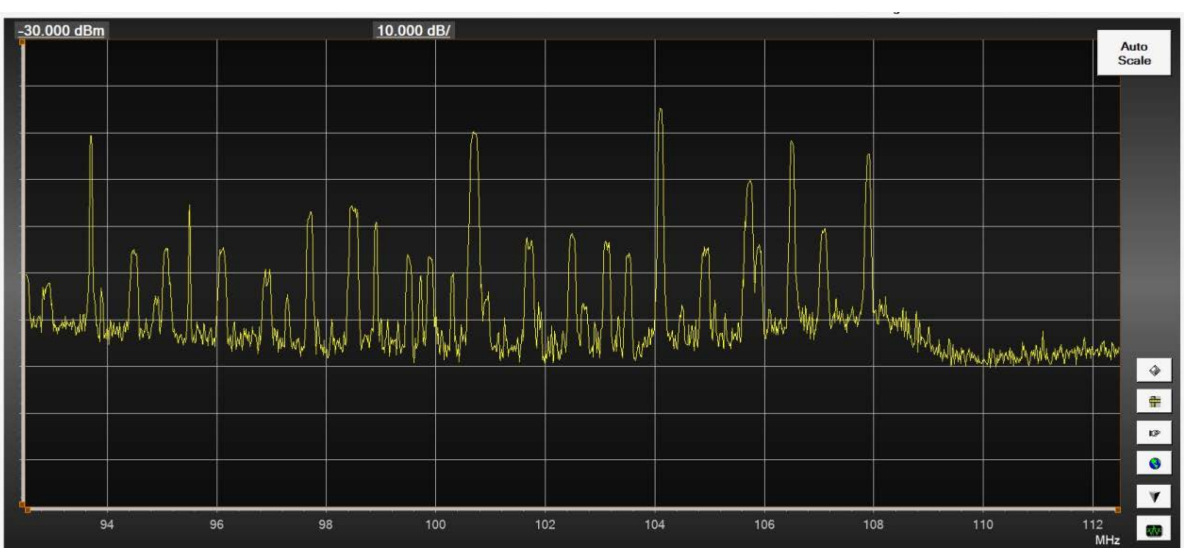

Figure 48. Spectrum Collected Near a High-quality Generator

In the second test case, a low-quality, commercial off-the-shelf inverter-generator was started and loaded at approximately 150 watts. Because of decreased shielding, inferior filtering and thinner materials, the same span of spectrum showed a markedly different result. The noise floor varied across the band and was significantly higher. The data in Figure 49 below shows an increased noise floor between -60 and -80 dBm.

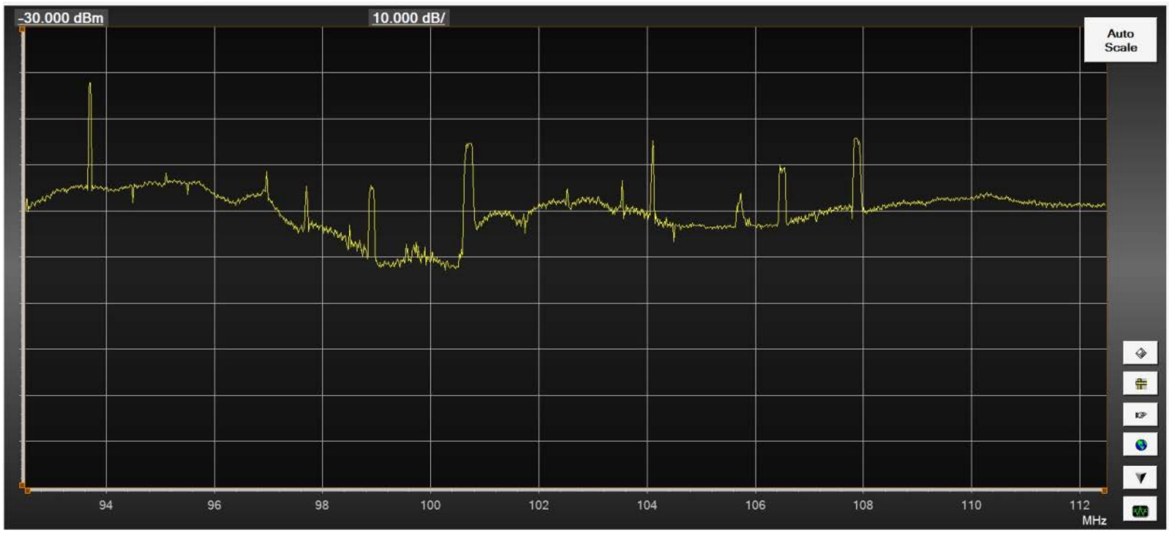

Figure 49. Spectrum Collected Near a Lower-quality Generator

The nursing home tornado response scenario held at the Eagle Electric compound was the only one during VG15 in which the researchers were able to collect human factors data in addition to RF data. The use of high-gain antennas with the Sennheiser receivers provided complete audio records for all channels, which allowed a more thorough analysis of the range of RF communications issues.

Table 16 provides a compilation of RF and interpersonal communications traffic derived from the audio streams for the incident command post and five of the tactical teams deployed during the scenario. Since the incident commander was not considered a tactical team, his interpersonal verbal communications were not included in the analysis.

Table 16. Measures of Information Lost, Transmitted by Interpersonal Voice and by Radio

TEAM	RADIO TRAFFIC						INTERPERSONAL TRAFFIC					
	Incorrect	Ignored/ lost	Request repeat	Total xmit	%total comms	Radio info loss	Incorrect	Ignored/ lost	Request repeat	Total xmit	%total comms	Verbal info loss
IC	0	14	3	261	--	7%	--	--	--	--	--	--
SAR1	0	5	1	9	11%	75%	0	0	0	72	89%	0%
SAR2	0	6	1	13	5%	58%	0	0	7	258	95%	3%
SAR3	0	13	0	21	13%	62%	0	0	2	145	87%	1%
TRIAGE	0	1	0	14	8%	15%	0	0	1	161	92%	1%
RECON	0	7	0	7	4%	100%	0	0	3	159	96%	2%

Losses are broken out by tactical team. IC= incident command, SAR=search and rescue, RECON=reconnaissance

As can be seen in the table, there were significant losses of radio communications throughout the scenario.

The causes of radio information loss between the instrumented tactical teams and the incident command post (IC) arose from four issue areas: ignored by the receiver, radio failure, RF path absorption or busy talk channel. See Table 17 for the categorical distribution of losses.

The ignored transmissions and busy channel losses were minor and inconsequential to the exercise, since the transmitting parties persisted in making contact despite the delays, and the receiving party (the incident commander) rapidly came up to speed with the rate of communications with the tactical units.

Table 17. Causes of Radio Traffic Loss

					CATEGORY					
TEAM	Ignored	Incorrect	Unintel-ligible	Channel Selection	Radio Failure	Busy Channel	Path Absorp-tion	Environ-mental Noise	Frequency Crosstalk	Noise Floor
IC	2					1	11			
SAR1	2						4			
SAR2							7			
SAR3					13					
TRIAG	1									
RECON					7					

A finding of particular interest was that RF path absorption was prevalent in the scenario. Figure 50 is a satellite image of the Eagle Electric Complex site. The colored lines overlaid on the image indicate the paths each tactical team traced during the exercise. SAR1 and SAR2 both experienced severe RF losses when behind or inside the structure. RECON did not transmit during their evolution, and thus had no record of RF loss.

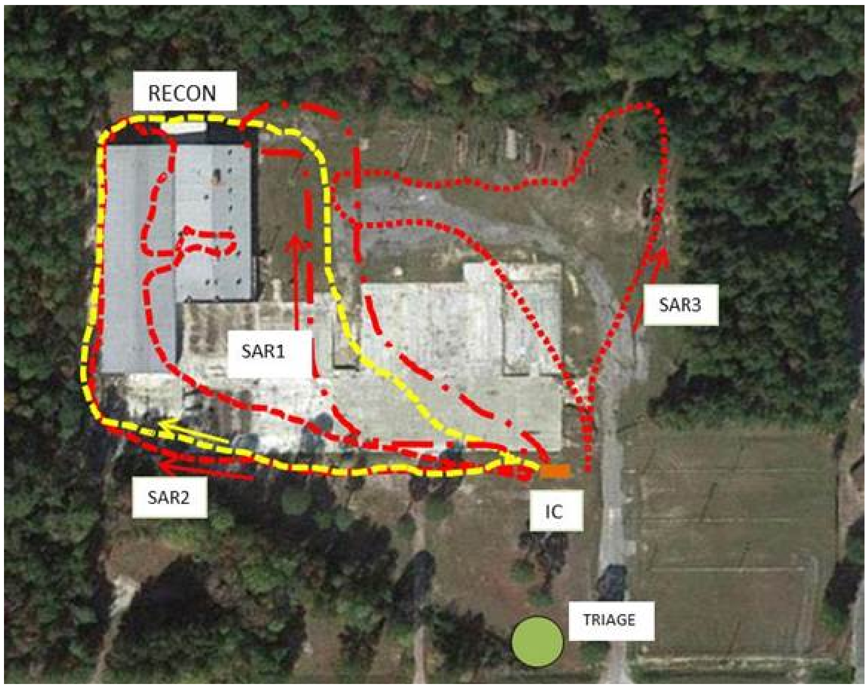

Figure 50. Paths taken by the various tactical teams during the Eagle Electric Nursing Home Tornado Response Scenario.

To test the effects of signal path and signal strength degradation in and surrounding the metal buildings that comprised the Eagle Electric venue, the researchers used a local fire department portable radio and a stationary Keysight RF sensor to measure relative power from different transmit locations.

The buildings were multi-room metal fabricated structures with cinder block interior room walls. Five locations were selected from within the building and five locations were selected from outside the buildings. The radio was tuned to the same simplex frequency used during the exercise, 851.6875 MHz. Figure 51 shows an overhead view of the location of the transmitter at each test position. The receiving RF sensor remained stationary.

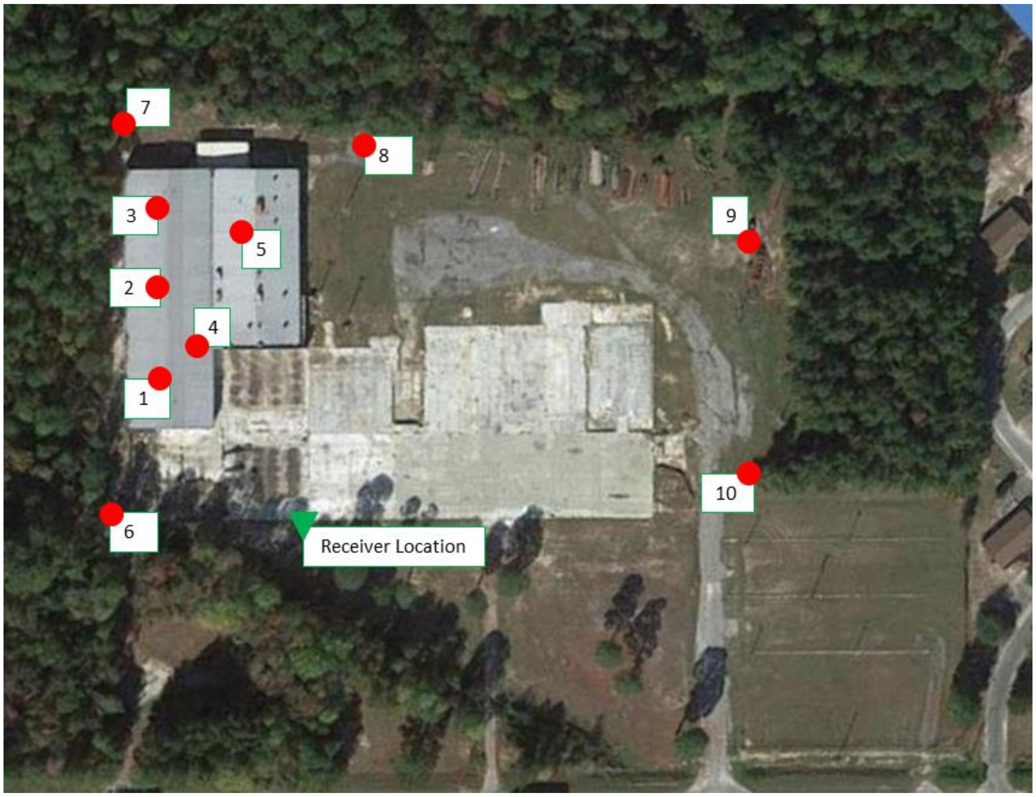

Figure 51. Transmitter Locations for Signal Degradation Test at Eagle Electric (Courtesy of Google Earth)

Relative power received from a transmitter is proportional to the square of the distance between them assuming consistent atmospheric conditions and unimpeded line of sight. The formula shown in Equation 1 represents that relationship:

Equation 1

$$\frac{P_r}{P_t} \propto \frac{1}{(1-d)^2}$$

In this equation, *Pr* is the received power, P_t is the transmitted signal power, and *d* is the distance between the transmitter and the receiver. The outdoor locations with clear line-of-sight to the receiver (positions 6, 8, 9 and 10) exhibited excellent correlation when comparing received signal strength to distance (squared) as shown in Table 18. A score of 1.0 indicates a perfect correlation on a scale from 0 to 1.

Table 18. Received Signal Strength Comparison From Outside the Building

Location	Signal Level (dBm)	Distance from Receiver (feet)
6	-28.6	214
8	-38.6	429
9	-48.1	602
10	-49.7	539
	Correlation:	0.96

The indoor locations (positions 1 through 5) demonstrated very poor correlation as shown in Table 19. The building caused unpredictable signal path loss and signal strength degradation.

Table 19. Received Signal Strength Comparison from Inside the Building

Location	Signal Level (dBm)	Distance from Receiver (feet)
1	-57.3	210
2	-63.5	353
3	-56.3	435
4	-42.8	263
5	-46.1	307
	Correlation:	0.35

The indoor locations (positions 1 through 5) and the outdoor location that were not line-of-sight experienced significant signal degradation as shown in Table 20. Compared to a similar distance transmission with no obstructions (position 8), all transmissions from within and behind the building were severely limited in their effectiveness. These RF measurement results match closely with the findings of the HF researchers, which noted that nearly all communications between the tactical teams and the command staff were degraded (or non-existent) when teams entered the building or traversed behind the structure.

Table 20. Signal Degradation from Transmissions Within and Behind the Metal Building

Location	Signal Level (dBm)	Distance from Receiver (feet)	Signal Degradation
1	-57.3	210	-99.7%
2	-63.5	353	-99.8%
3	-56.3	435	-98.3%
4	-42.8	263	-85.7%
5	-46.1	307	-90.9%
7	-48.7	514	-86.0%

Scenario 3: Georgetown Airport C2 and Medevac Operations

Several hundred personnel from multiple agencies were involved in operations at the Georgetown Airport, primarily to provide Command and Control (C2) and conduct medevac operations. The 2nd Battalion, 151 Aviation Regiment from McEntire JNGB flew nine helicopters in support of multiple VG-15 exercise scenarios throughout the state, to include medical transport of role players to the airport for notional treatment by Carolinas MED-1, a large mobile hospital complex.

Carolinas MED-1, the first-of-its-kind mobile hospital, is designed to provide comprehensive patient care at the site of a disaster or other mass casualty incident (see Figure 52). MED-1 is owned by Carolinas HealthCare System. MED-1 has 100 members; however, the size of the on-site staff is dependent on the nature of the disaster they are supporting. DHS funded and launched MED-1 to provide large-scale medical support during Hurricane Katrina. MED-1 travels as two 53-foot tractor-trailers plus other support vehicles, to include a mobile satellite system. MED-1 also operates a fleet of four helicopters, five aircraft and 30 ambulances. One aircraft was used during the exercise to deliver medical professionals to the site.

Figure 52. Inside MED-1

MED-1 creates a very large communications footprint when fully operational. Voice communications is provided by the North Carolina Viper system, a Motorola APX 7000 that provides dual band 800 MHz and UHF. The North Carolina Viper system could not communicate with the South Carolina Palmetto system, although they are both Motorola 800

MHz radios. Therefore, MED-1 borrowed some Palmetto systems (Motorola XTS 5000) to allow coordination with local agencies. Bluetooth headsets were used with the radios. Iridium satellite phones and cell phones were also used.

A Winegard satellite antenna system (Figure 53) provides internet access for the transmission of medical data and telemedicine via a 5 GHz communications channel. Dedicated Wi-Fi hotspots allow MED-1's 13 laptops and 13 ipads to connect and share data. A General Electric Ultrasound system transmits images directly via Wi-Fi. MED-1 also has a Direct TV satellite to monitor national news channels.

Figure 53. MED-1 Communications Antennas

Several other agencies were also operational at the Georgetown Airport, to include the South Carolina Air National Guard Security Force that managed overall airfield operations and security. Georgetown Sheriff's deputies were also present, although their communications devices were limited to their Palmetto radios and personal cell phones.

The team from the 169th Communications Flight from McEntire JNGB and the Fort Belvoir-based 29th Infantry Division operated the Joint Incident Site Communication Capability (JISCC) and created one of the largest communications footprints at the airport. The JISCC is made up of communications equipment that provide Internet access and telephone support to military, federal, state and local emergency management agencies during the disaster response. The equipment includes servers, laptops, radios, satellite dishes and telephones. In the event of a local or state-level emergency, the JISCC allows responders to coordinate with each other locally and with command and control elements statewide.

Georgetown Airport Analysis

The researchers set up four RF sensors around the Georgetown Airport Exercise venue. This venue was host to a wide range of military activity, including airfield operations, air traffic control, fire rescue, military police and a field hospital established by Carolinas MED-1, a mobile hospital for disasters.

The Georgetown County public safety agencies use the South Carolina Palmetto 800 MHz hybrid radio system for primary communications between law enforcement, fire and EMS agencies. The RF environment at the airfield showed no signs of interference with the 800 MHz radio system. As shown in Figure 54, the individual frequencies of the Palmetto system are clearly separated and defined, and there are no signs of interference between signals. Resolution bandwidth was increased to capture this image, and although Marker 3 appears to be consumed by the energy transmitted by the peak labeled as Marker 11, a more detailed investigation showed the two frequencies were clearly separated.

Figure 54. Clear Communications within the Palmetto 800 System as Recorded at the Georgetown Airport Exercise

The researchers did observe evidence of RF interference due to spurious emissions by helicopter airfield communications (from ground to air). The helicopter airfield communications were handled between 140.75 and 148.5 MHz. The transmitter for this traffic was a high-power military radio connected to a high-gain antenna. The high amplitude of the signal measured by the FieldFox analyzer is shown in Figure 55.

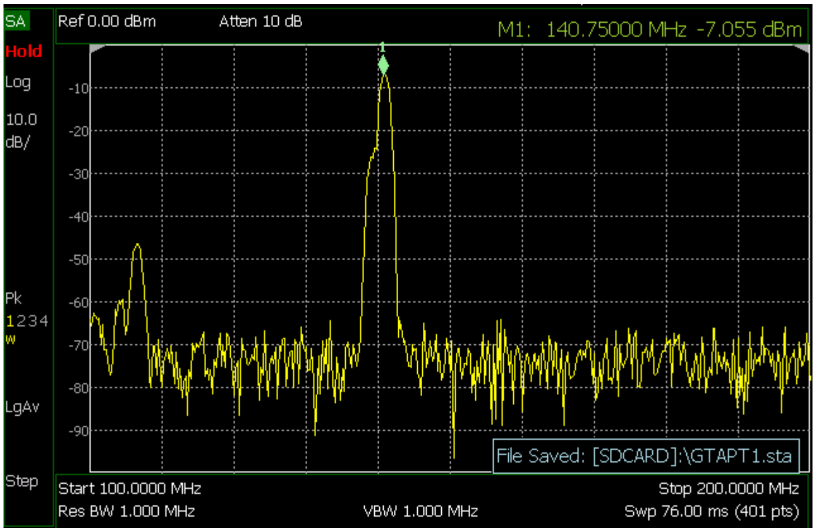

Figure 55. Military Radio Traffic Detected at a High Amplitude at 140.75 Mhz

The transmitter exhibited high-level, spurious emissions across the VHF high band. In Figure 56, high-amplitude RF signals can be seen spanning from 140.75 MHz (the source) to 160 MHz. These signals introduced high-level energy into the civilian public safety VHF band. While it had no impact on public safety agencies in the area (they all operated in the 800MHz band) during the exercise, other agencies that might have been operating in the 150+ MHz bands would have been effectively silenced during the military transmissions.

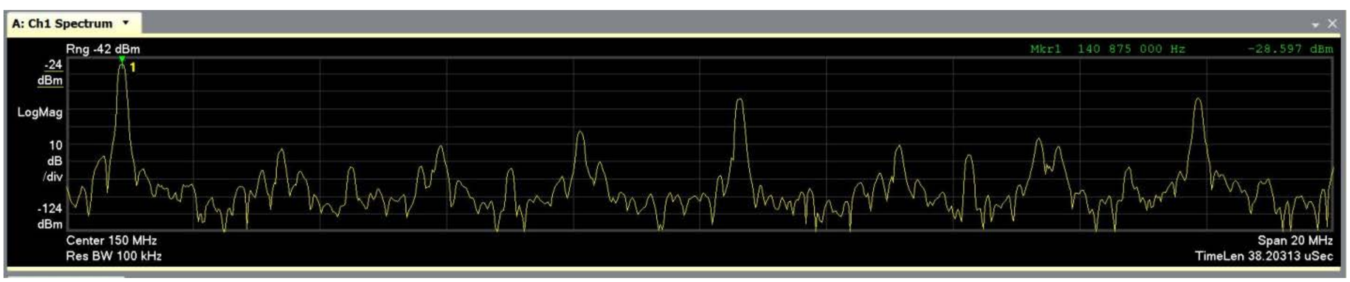

Figure 56. Broadband Interference in the VHF High Band Caused by High Power Military Transmissions

Hartsfield-Jackson Atlanta International Airport Mock Disaster Exercise

The Atlanta Fire Rescue Department (AFRD) conducted a mock disaster exercise on April 15, 2015 in compliance with FAA requirements for all major airports to conduct firefighter certification exercises every three years. The researchers monitored the RF spectrum, while more than 100 firefighters and other first responders extinguished a burning plane simulator in one area of the airport's training compound and then evacuated and treated nearly 100 role players from another plane, as shown in Figure 57.

Figure 57. First Responders Evacuate 100 Role Players During Mock Plane Crash

The purpose of the exercise was to test the firefighter response time, to test and validate first responder equipment, and to take a snapshot in time of AFRD's overall state of readiness. In addition to the large contingent of Atlanta airport public safety personnel, fire departments from the local community also participated in this training. This included firefighters and EMS personnel from Grady Memorial Hospital, Clayton County, and the cities of Riverdale and Forest Park. Their participation helped to test mutual aid response procedures, in particular the process of safely introducing local first responder vehicles and equipment into the Atlanta airport airfield in the event of an actual disaster. Approximately 50 vehicles from multiple agencies were called to the scene throughout the course of the exercise. The specialized Aircraft Rescue and Firefighter (ARFF) equipment, required by the FAA, included several fire engines and trucks and several large mass casualty response and transportation vehicles. The exercise was monitored and controlled by the training facility operations center and the Atlanta airport Mobile Command Post (MPC).

This exercise was not conducive to the same level of human factors evaluation the researchers had conducted in previous exercises, since no access to the exercise participants prior to or during the disaster scenario was provided. In addition to the first responders and role players, local and national media were also present, to include CNN and Fox News. Nearly 100 civilians were also invited to observe the training, and their steady use of cell phones and tablets to take and share photos and videos also contributed to a robust RF environment. The researchers selected the best vantage point, as shown in **Figure 58**, for positioning equipment to monitor and record the RF spectrum.

Figure 58. RF And HF Monitoring Stage at the Atlanta Airport Training Site

The exercise parameters were:

- Number of participants:
  - 100+ firefighters and paramedics.
  - 20+ law enforcement officers.
  - 20+ airport support staff.
  - 100 crash victim role players.
  - 100+ civilian observers and news media.
  - Average PAN count was 2 devices per person.
- Equipment used by participants:

- 50+ vehicles (fire apparatus, ambulance, rescue, command, police).
- Full turnout gear.
- Portable floodlights with generators.
- Full SCBA breathing gear.
- 800MHz portable radios.
- Personal Cellphones.
- Rescue gear.

Airport Mock Disaster RF Analysis

All agencies involved in the exercise, including the mutual aid fire departments from surrounding communities, used the Atlanta Public Safety P25 (Phase 1) digital 800 MHz trunked radio system for all communications. With all frequencies used by the system known, the spectrum was scrutinized while on scene and there were no signs of interference. This included an analysis of system carrier frequencies, separation, harmonics and spurious emissions.

With the system being a digital trunked system, the frequencies detected at the exercise were processed using demodulation algorithms to determine error rates of the digital data. As shown in Figure 59, an average digital error rate of 1.9% was observed. This is excellent and results in nearly undetectable flaws in the radio traffic.

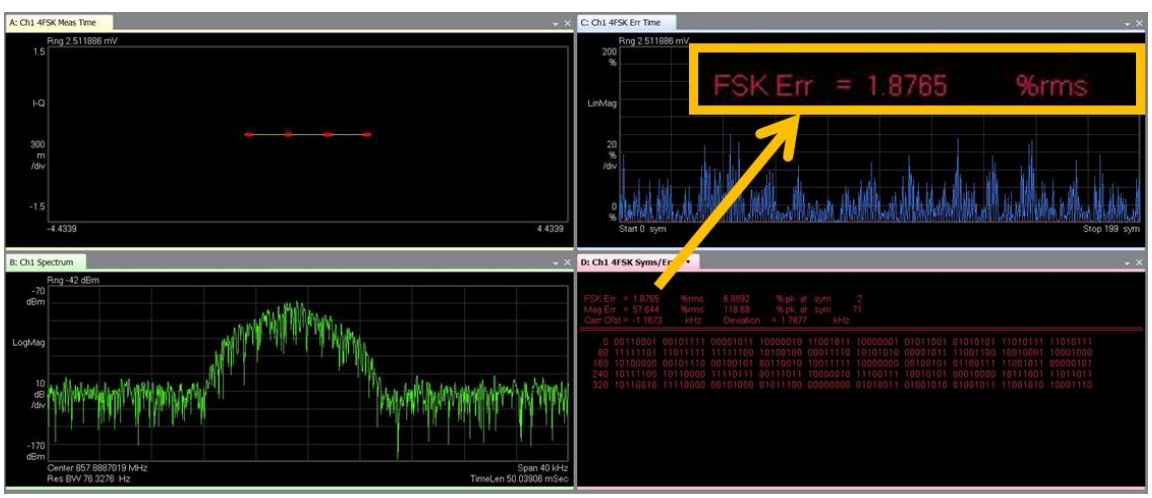

Figure 59. Digital Demodulation Analysis of the 800 MHz Channels Used at the Atlanta Airport Exercise

This exercise did not present significant sources of interference due to the prior planning of the event, the common communication system, and the adequately-spaced set up of auxiliary electrical power equipment around the scene.

Guardian Centers Subway Explosion Response Exercise (GC-15)

The scenario for this exercise was an explosion in a subway station with numerous casualties. More than 50 first responders from Middle Georgia participated in the exercise at Guardian Centers on April 28, 2015. Complicating the emergency scene was the discovery of a suspicious package containing a secondary device. Guardian Centers' quarter mile subway is a realistic, controlled venue that replicates a working subway platform and tunnel. Following a large simulated explosion, the subway remained cloaked in darkness and smoke.

Participating agencies in the technical rescue and hazardous material response exercise included the fire departments from Houston County, Perry and Warner Robins. Perry (Fire Department) was the first on scene and implemented its incident command system. Additional fire units and specialized equipment followed, including the Houston County hazardous material team (Figure 60) and a working element of the Georgia Search and Rescue Team.

Figure 60. Houston County, GA HAZMAT Team Enters the Subway Station

Law Enforcement participation included officers and deputies from Perry, Warner Robins, Centerville, Macon-Bibb County and Houston County. The Macon-Bibb County Sheriff's Office deployed its Mobile Command Post (MCP), and state level support was provided by the Georgia State Patrol and the Georgia Bureau of Investigation (GBI). The Houston County Emergency Medical Service (EMS) responded with three ambulances. Additionally, the Houston County Communications Manager provided support from the Guardian Centers Emergency Operations Center (EOC).

The Macon-Bibb MCP provided a live link to the Georgia Emergency Management Agency (GEMA) and local EMA personnel. The Houston County EMS Director implemented a real-time internet-based connection with WebEOC for incident reports and resource tracking for eight separate medical facilities throughout Middle Georgia.

The primary radio communications between first responders was the Houston County P25 Phase 1 800 MHz trunked digital radio system and supplemented with mobile phones. UHF hand-held radios were used by the Guardian Centers for exercise control.

Additional technologies included a wireless GBI bomb squad remote F6B robot that entered the subway to investigate a suspicious package, Google Glass type body worn camera worn by Centerville Police, and an Amateur Radio Emergency Services (ARES) mobile station.

VSG-Unmanned, one of only two companies in Georgia with an FAA blanket Certificate of Authorization (COA) to operate in the National Airspace for commercial purposes, flew a drone both in the subway and outside, streaming live video to the EOC. New technology used during the exercise included a cloud-based application that allows the public to establish a two-way video and voice connection to 911 Centers. BeamSmart provided cell phones with their app to Mercer University students, who participated as subway victims.

GC-15 Analysis

The GC-15 exercise was larger and more complex than the tornado response scenario, and thus evidenced different patterns of signal loss and signal degradation than that exercise. Table 21 provides a compilation of RF and interpersonal communications traffic derived from the audio streams for the incident command post and five of the tactical teams deployed during the scenario. Since the incident commander was not considered a tactical team, his interpersonal verbal communications were not included in the analysis. The police-on-scene was the responder who was present on the subway platform at the time of the notional explosion, and so was also not a team. She was responsible for calling in the incident, maintaining communications with the incident command post as the response evolved, and providing on-scene policing until she was evacuated by the search-and-rescue teams when they arrived.

Table 21. Measures of Information Lost, Transmitted by Interpersonal Voice and by Radio

					RADIO TRAFFIC		INTERPERSONAL TRAFFIC					
TEAM	Incor-rect	Ignored/ lost	Re-quest repeat	Total	% total comms	Radio info loss	Incor-rect	Ig-nored /lost	Re-quest repeat	Total	% total comms	Verbal info loss
IC	1	41	8	366	--	13%	--	--	--	--	--	--
Police on-scene	1	0	1	56	--	4%	--	--	--	--	--	--
Interior 1	1	35	6	96	34%	47%	0	0	2	185	66%	1%
Interior 2	0	4	2	68	16%	9%	0	0	5	368	84%	1%

Losses are broken out by tactical team. IC= incident command. SAR=search and rescue

As with the VG15 exercise, there were significant losses of radio communications documented throughout the scenario. Signal path absorption was extensive, and was the major cause of radio information loss between the instrumented tactical teams and the incident command post (IC). However, there was evidence of channel selection errors that arose when the tactical channel became overburdened during the first part of the exercise. Table 22 presents the distribution of losses by cause.

Table 22. Causes of Radio Traffic Loss

						CATEGORY				
TEAM	Ignored	Incor-rect	Unintel-ligible	Channel selection	Radio fail	Busy channel	Path absorp.	Envir. Noise	Freq crosstalk	Noise floor
IC	1	0	0	0	0	0	49	0	0	0

TEAM	Ignored	Incor-rect	Unintel-ligible	Channel selection	Radio fail	Busy channel	Path absorp.	Envir. Noise	Freq crosstalk	Noise floor
					CATEGORY					
Police on-scene	0	0	0	0	0	0	2	0	0	0
Interior1	0	0	0	0	0	0	42	0	0	0
Interior2	1	0	0	0	0	0	5	0	0	0

A satellite image of the GC mock subway station site is shown in Figure 61. The long purple rectangle represents the four subway cars located at the station platform. Another set of cars was located on a second set of tracks in the direction of the yellow arrow on the picture. A third set of cars was overturned in the area past these cars.

The colored lines overlaid on the image indicate the paths each tactical team traced during the exercise. All tactical radios experienced significant RF losses inside the structure. Interior1 entirely lost communication when moving north toward the second set of train cars.

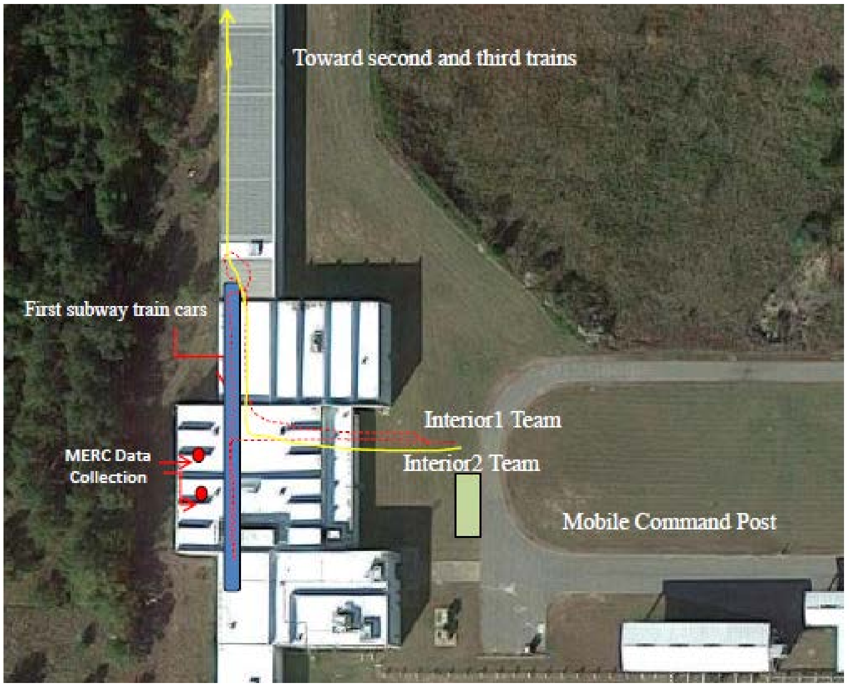

Figure 61. Tracing the Path of Two Instrumented SAR Teams (Courtesy of Google Maps)

The researchers used a Harris portable radio and a stationary Keysight FieldFox handheld spectrum analyzer to measure relative power from different transmission locations. This was done to test the effects of signal path and signal strength degradation in and surrounding the hardened metal buildings that made up the subway venue.

The buildings were multi-room metal fabricated structures with cinder block interior room walls. Ten locations were selected from within the building and three locations were selected from outside the buildings in order to establish correlation. The radio was tuned to NIFOG 8TAC91D (851.5125 MHz) in the same band used during the exercise by the Houston County P25 Trunked Radio System.   Figure 62 shows the interior location of the transmitter at each test position. Figure 63 shows the exterior locations. The receiving RF sensor remained stationary.

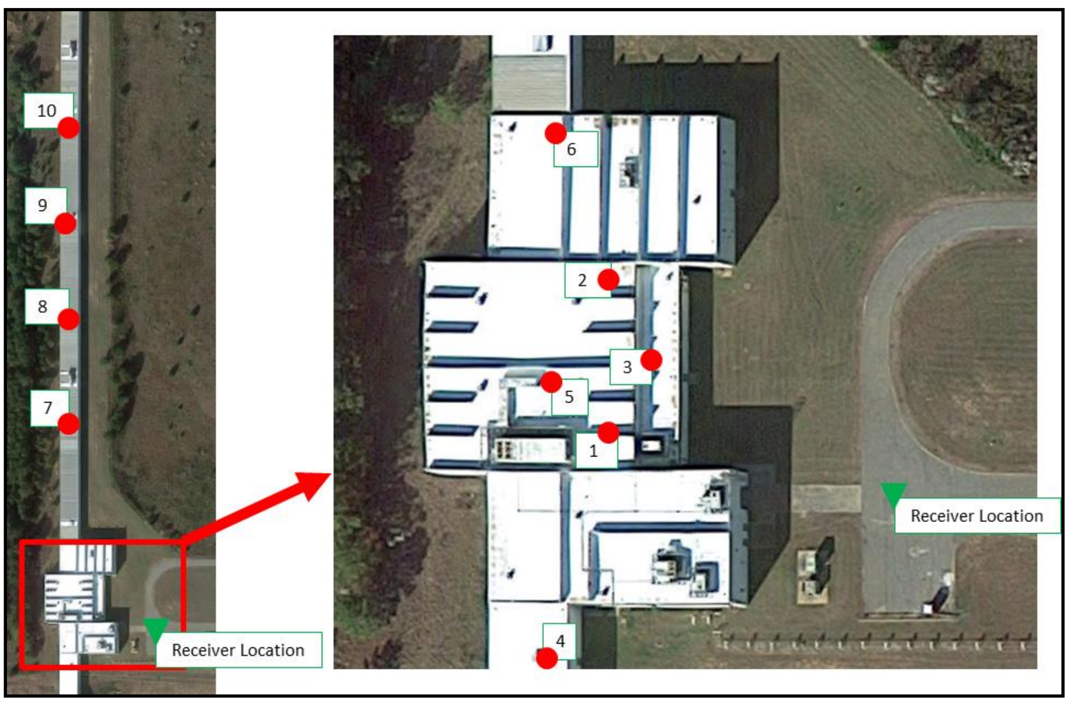

Figure 62. Interior Transmitter Locations for Signal Degradation Study (Courtesy Google Earth)

Figure 63. Exterior Transmitter Locations for the Signal Degradation Study (Courtesy Google Earth)

As previously discussed, relative power received from a transmitter is proportional to the square of the distance between them, assuming consistent atmospheric conditions and unimpeded line of sight. The formula in Equation 1 represents that relationship.

The outdoor locations with clear line-of-sight to the receiver (positions A, B and C) exhibited excellent correlation when comparing received signal strength to distance (squared). A score of 1.0 indicates a perfect correlation on a scale from 0 to 1 (see Table 23).

Table 23. Received Signal Strength Comparison from Outside the Tunnel at Guardian Centers

Location	Signal Level (dBm)	Distance from Receiver (feet)
A	-46.7	488
B	-52.9	1092
C	-47.0	448
	Correlation:	0.997

The indoor locations (positions 1 through 10) demonstrated very poor correlation as can be seen from the data in Table 24. The materials of the building caused severe and unpredictable signal path and degradation losses.

Table 24. Received Signal Strength Comparison from Inside the Tunnel at Guardian Centers

Location	Signal Level (dBm)	Distance from Receiver (feet)
1	-55.6	132
2	-65.7	167
3	-34.9	120
4	-71.7	204
5	-58.9	160
6	-69.5	242
7	-72.1	444
8	-70.8	607
9	-88.1	775
10	-88.6	963
	Correlation:	0.32

The indoor locations (positions 1 through 10) experienced significant signal degradation. Compared with transmission over a similar distance with no obstructions (position 8), all transmission from within the building was severely limited in effectiveness.

Again, these RF measurement results match closely with the findings of the HF researchers, which noted that nearly all communications between the tactical teams and the command staff were degraded (or non-existent) when teams entered the building or traversed northward through the structure.

Table 25. Signal Degradation from Transmissions within the Hardened Metal Subway

Location	Signal Level (dBm)	Distance from Receiver (ft)	Signal Degradation
1	-55.6	132	-99.1%
2	-65.7	167	-99.9%
3	-34.9	120	-25.7%
4	-71.7	204	-99.9%
5	-58.9	160	-99.5%
6	-69.5	242	-99.9%
7	-72.1	444	-99.8%

Location	Signal Level (dBm)	Distance from Receiver (ft)	Signal Degradation
8	-70.8	607	-99.5%
9	-88.1	775	-99.9%
10	-88.6	963	-99.8%

Research Question Results

As the analysis of data from the naturalistic experiments has shown, the effect on first responders of RF signal loss and degradation within their PAN is determined by the complex interactions among technologies, environments, tactics, human factors and socio-technical systems. The extent of this effect is illustrated in the answers to the original research questions.

Within the scope of current and future wireless communications technology used by first responders at emergency scenes, what are the causes of RF signal loss and degradation?

The first hypothesis based on this question was: "RF carrier signal amplitude loss is measurable in predictable types of emergency scenarios." This hypothesis relates directly to absorption/reflection/refraction of RF signals on the pathway between the transmitter and receiver. The AAR data from the DHS library shows that complex emergency scenarios are as commonly found in rural environments as in urban environments, and are addressed within and outside structures of varying construction. Based on analysis of the AAR data, the following types of scenario environments represent the range of areas in which first responders can expect predictable types of RF losses:

- Outdoor environments:
  - Urban canyons – inner city areas, such as Manhattan in New York City, where multi-story concrete/steel buildings interrupt line-of-sight RF transmission, and there are fewer reflective paths between transmitter and receiver.
  - Noisy urban environments – locations having steady sources of electromagnetic fields, such as multiple high-tension lines, power transfer stations, high-output generators, etc.
  - Subterranean environments – subways tunnels, utility tunnels, bunkers, caves.

- Rural canyons – land forms that interrupt line-of-sight RF transmission; e.g., mountains, arroyos, ravines, etc.
- Out-of-range areas – typically wilderness, rural or aquatic areas that are at or beyond the range of the closest operational wireless repeater.

- Indoor environments:
  - High-rise buildings.
  - Concrete/steel.
  - Steel sheathing, especially large open areas with principle axes (waveguide effect).

Each type of environment is susceptible to different types of signal path loss as described in http://www.radio-electronics.com/info/propagation/path-loss/rf-signal-loss-tutorial.php.

- Free space loss: The free space loss occurs as the signal travels through space, without any other effects attenuating the signal, it will still diminish as it spreads out.
- Absorption losses: Absorption losses occur if the radio signal passes into a medium that is not totally transparent to radio signals.
- Diffraction: Diffraction losses occur when an object appears in the path. The signal can diffract around the object, but losses occur.
- Multipath: In a real terrestrial environment, signals will be reflected and they will reach the receiver via a number of different paths. These signals may add or subtract from each other depending upon the relative phases of the signals. If the receiver is moved, the scenario will change and the overall received signal will be found to vary with position. Mobile receivers will be subject to this effect, which is known as Rayleigh fading.
- Terrain: The terrain over which signals travel will have a significant effect on the signal. Obviously hills that obstruct the path will considerably

attenuate the signal, often making reception impossible. Additionally, at low frequencies, the composition of the earth will have a marked effect. Dry sandy terrain gives higher levels of attenuation.

- Buildings and vegetation: For mobile applications, buildings and other obstructions including vegetation have a marked effect. Not only will buildings reflect radio signals, they will absorb them. Cellular and 800 MHz communications are often significantly impaired within buildings. Trees and foliage can attenuate radio signals, particularly when wet.
- Atmosphere: The atmosphere can affect radio signal paths. At lower frequencies, especially below 30 – 50 MHz, the ionosphere has a significant effect; refracting them back to Earth. At frequencies above 50 MHz and more the troposphere has a major effect, refracting the signals back to earth as a result of changing refractive index. For UHF broadcast, this can extend coverage to approximately a third beyond the horizon.

As the signal strength analysis from VG15 and GC15 showed, structural sources of signal attenuation were a major cause of RF loss, while line-of-sight atmospheric losses in all exercises were predictably small. Hypothesis H1a was confirmed.

Signal degradation due to spectral interferences, as described in hypothesis H1b was also measurable in predictable situations, though it had less impact on first responders in the exercise scenarios used as the basis for this research. In the VG15 airport scenario, the researchers documented significant broadband interference in the public safety VHF band due to near-channel interference from a military transmitter. It did not affect first responder communication because that band was not used by any of the participating agencies. First responder agencies that use VHF bands should be aware of potential interference when performing joint operations with military ground-to-air communications. This finding confirmed the H1b hypothesis.

The third hypothesis in this research question, anticipating significant digital packet loss was not confirmed in any of the experimental scenarios. Demodulation analysis showed less than 2% loss due to this source.

How much information is lost due to each of the sources of signal loss and signal degradation?

Radio signal attenuation was a considerable source of information loss at the VG15 and GC15 exercises. During the nursing home rescue scenario in VG15, the use of hand-held mobile radios in simplex mode for the IC and tactical teams reduced the RF transmit-and-receive power at both ends to the point that 58% of total radio traffic was absorbed by the surrounding structures while teams were in the primary tactical zone.

The amount of radio information lost by instrumented tactical teams from this source alone was 32%. The instrumented teams in the subway explosion scenario (GC15) lost even more information from RF signal absorption, even though the IC was located in a mobile command post equipped with high-powered repeaters and antennas.

Table 26 summarizes the radio traffic loss from instrumented teams at each scenario. All of the RF losses experienced by the instrumented tactical teams were due to signal loss resulting from structural transmissivity of the buildings surrounding them. Given these results, it is evident that analog and digital radio signal loss and degradation has a measurable effect on information loss in the tactical environment. Hypothesis H2 is therefore confirmed.

Table 26. Summary of Radio Traffic Losses from Instrumented Tactical Teams at three Exercise Scenarios

Scenario	Total Traffic	Total Radio Traffic	% Info by Radio	Radio Traffic Lost	% Radio Info Lost	RF Losses	% Radio Losses from RF
GC14-shoring	416	82	20%	11	13%	0	0
VG15-eagle	859	64	7%	34	53%	11	32%
GC15	717	164	23%	48	29%	47	98%

What proportion of the total information flow at the tactical level is lost due to radio traffic losses?

Radio traffic volume was similar between the GC14 and GC15 scenarios at approximately 20% of the total flow of information in the tactical scene. The nursing home scenario in VG15 had a much lower proportion of radio traffic, which was reflective of the amount of difficulty with radio communications faced by three of the five instrumented teams, as well as the limited need for radio in the two remaining teams who worked short-range, outdoor tactical environments.

The RF losses, as a proportion of the total tactical information flow for each team, reflect the difference between outdoor (line-of-sight) and indoor tactical environments. The GC14 team worked on the outside of the structure with clear line-of-sight to the tactical command trailer. They experienced no difficulty with RF signal attenuation, but ambient noise and the use of SCBA combined to reduce the radio traffic information by 13%. On the other hand, the GC15 teams lost 29% of their radio traffic, almost all of which was due to RF signal attenuation.

The proportion of total information lost due to RF signal loss and degradation was a small proportion of the total information flow within any of the tactical scenes, with a maximum of 6.5% lost at GC15. However, this was a significant portion of the radio traffic, which has the greatest impact on situational awareness and safety. Hypothesis H3 is thus confirmed.

How much is first responder workload, both physical and cognitive, increased for a given amount of radio signal loss and degradation, compared to the total loss from all types of signals?

To discuss the effect of radio traffic losses on mental and physical workload, it is important to assess the workload experienced by the complete cohort of first responders from whom data was collected. Table 27 provides a breakdown of median scores (n=81) from each of the questionnaires used at the scenarios. The ratio of median score to maximum score is given in the table for the entire cohort to allow comparison between questionnaire instruments.

As can be seen in the table, the physical and mental stress scores between the instruments are very comparable. As a group, the median scores indicate moderate levels of workload and time pressure. The median absolute deviation of the TLX scores for Mental Stress, Physical Stress, Temporal Stress and Effort (centering around 4) are comparable to deviations of +/- 1 in the HVHF domains.

The median TLX scores for Performance and Frustration show very low input from those domains, reflecting the well-structured nature of the exercises where roles and responsibilities are well-defined in advance. The high scores in the HVHF domains of Complexity and

Predictability are indicative of the complex nature of the exercises and the challenges of coordination with outside agencies.

Data was collected from nine tactical teams, involving 23 first responders, among the three exercise scenarios. The results are shown in Table 27. As expected, the tactical teams show a different level of stress than the whole-group scores indicated, and with much less variance. Where the rating domains were similar between HVHF and TLX, such as physical stress and mental stress scores, both showed similar responses.

For example, physical stress ratings showed a significant increase, consistent with the difference between tactical actors and responders having more sedentary roles. The mental stress ratings were likewise consistent, though they showed no appreciable difference from the cognitive stresses of the wider group of responders. The tactical teams found the scenarios much less predictable, expended much greater effort, and experienced greater frustration than the wider group as well.

A comparison of the data from the nine team leaders shows expected differences and similarities with their team members. Team leaders had much greater clarity in the mission than their team members, and felt greater time pressure. There was a more moderate increase in the physical stress and effort they had to exert compared to their team members. However, examination of the results in Table 27 and Table 28 shows there was no correlation between the physical or cognitive workload and the information loss among team leaders from the three exercise scenarios. Hypothesis H4b is thus not supported by the results.

Table 27. Median Ratings of Human Factors Characteristics that Impact Workload

	Complexity rating	Predictability rating	Clarity rating	Time rating	Mental stress rating	Physical stress rating	Tlx mental	Tlx physical	Tlx temporal	Tlx performance	Tlx effort	Tlx frustration	Max borg cr10
Max Rating	7						0	0	0	0	0	0	0
GC14	6	.5	.5	.5	.5		2	4	.5		2.5	1	.5
VG15	6						4	3	6		4	4	
GC15	5	4	4	3	4	3.5	10	5.5	8	5.5	11	4	5
ALL	6						2	4	1		4	1	
MAD	0	0	0	0	0	0	0	0	0	0	0	0	0
RATIO	0.86	0.86	.43	.71	.71	.71	.60	.70	.55	.35	.70	.55	.50
Delta	0 0	0 .15	0.07	.14	0.07	0.14	0.05	0.17	0.07	0.05	0.14	0.20	0 0

MAD is the median absolute deviation, a robust measure of the data variability that limits the impact of outliers. RATIO is the ratio of the median rating to the maximum score in each column. The data were compiled from the results of questionnaires given to first responders at each of the exercise scenarios**.** Data was compiled from 23 first responders who made up 9 tactical teams within the three scenarios.

Table 28 Data from Nine Team Leaders

GC14	6	5	3	6	6	5	11	14	16	11	14	11	7
GC15	5	5	2	3	3	6	11	11	11	7	8	11	3
MAD	0.0	0.5	1.0	1.0	1.0	0.5	2.5	3.0	2.0	2.0	2.0	3.0	1.5
Delta	0.0	0.0	-0.14	0.08	0.0	0.08	0.03	-0.02	0.25	-0.02	-0.05	0.0	0.10

DISCUSSION

Emergency exercises were purposefully selected for the experiments to reflect real-world environments, rather than laboratory situations. This naturalistic experimental approach provided excellent correspondence to situations and phenomena commonly experienced by first responders.

The data collection scenarios included outdoor and indoor environments, rural and urban areas, environments with and without high levels of RF noise, and areas of low RF transmissibility. The collected data provided clear measurements of the types of technology issues that can be expected in these situations and the human impact that such limitations to radio communications can have on first responders.

Technology Issues

Land mobile radios are the primary source of communications used by first responders. Because they are tightly regulated and subject to robust design standards, they inherently avoid most types of interference. Co-channel and adjacent signal interference are rare because FCC licensing of radio frequencies adequately separates channels depending on power levels and geographic location of the transmitters. Transmitter spurious emissions are stringently controlled by FCC hardware certifications. Intermodulation was likewise not observed in any of the primary responder communication systems used at the exercise scenarios due to adequate filtering and antenna installations at the repeater sites.

The devices that operated in the low-power ISM bands, such as Bluetooth devices and Wi-Fi were also not hindered in their operations. This is because: 1) those standards are designed to accommodate interference through error-checking and retransmissions; and 2) a first responder density of 30 people separated by 30 feet does not tax the limits of the wireless standards for those bands. One can expect slower data transfer rates if more of these devices are more tightly co-located and the data transfer rates required by each ISM device were much higher than the typical devices found currently at tactical scenes.

However, low-power broadband devices are typically not designed to emit enough power to transmit farther than 10 meters, making signal co-location interference, even at high data packet densities, unlikely at that range. Also, realistic tactical scenes rarely have a greater density of first responders than this, thus limiting the potential for any significant digital losses due to low-power, ISM-based devices. An overloaded situation was created at the GC15 subway, where all 50 of the participants were asked to stand within a circular diameter of 30 feet, key up their portable radios, and operate their smart phones at the same time while the researchers recorded the RF signal environment. Interference was insignificant even with this artificial overloading.

Even with well-designed wireless communications technology and infrastructure, other types of RF problems can and often do happen in emergency response situations. Signal absorption and refraction was evident in the VG15 Eagle Complex scenario and in the GC15 subway scenario. This is a common occurrence in metal structures and underground structures, among others.

There are many variables involved that determine the best radio to use in a particular structure, including transmission frequency, power, receiving antenna sensitivity and building layout (e.g., windows, doors). The findings from this research illustrate the importance of first responders having a portfolio of different types of communication systems available to mitigate such losses.

A particular set of frequencies may be ideal in one situation and not in another. This reality was reflected in the after-action report from the 2013 Navy Yard shooting in Washington, DC. First responders in an active shooter scenario reported almost immediate loss of tactical communications as they entered the building. This loss was only mitigated through the use of runners and by a high degree of training on the part of tactical teams.

In addition to RF interference, radio communications can be severely impaired by problems with infrastructure, such as improper communication systems set up and socio-technical problems involving technology training, situational training and mitigation planning. At the VG15 airport scenario, a military unit transmitting at power levels beyond what was required for clear communications created receiver saturation and harmonic distortion in the nearby public safety VHF bands. At the VG15 Eagle Complex scenario, a noisy generator caused a significant decrease in the signal-to-noise ratio (SNR) in the lower frequency bands.

These types of interferences can be mitigated with appropriate planning for antenna placement, power output and equipment maintenance.

Such problems continue to occur in real world events. The after-action reports from the 2003 Washington, DC sniper incident and from the 2009 Chino prison riot documented the difficulties faced by multiple agencies trying to communicate through interoperability gateways that were improperly set up. Even as late as 2013 during the Boston Marathon bombing response, the explosive ordinance disposal unit from the Massachusetts Army National Guard experienced interoperability problems due to limited training and experience.

Human Issues

Communication issues have a significant and predictable impact on first responders. Teams of responders moving into a tactical environment tend to maintain a sharp focus on accomplishing their assigned tasks. Training and experience reinforce their frequent use of radio communications with tactical leaders to support status monitoring and situational awareness outside the tactical envelope.

However, radio communications most often assumes a secondary priority for the tactical responders such that the team leaders continue to push toward their objectives even when radio communication becomes more difficult. Increases in the cognitive workload of tactical responders can reduce their awareness of risk and their ability to mitigate losses in radio communications. A cascade of events leading to negative outcomes can occur when this increased risk is amplified by loss of situational awareness outside the tactical envelope.

This type of risk cascade is exemplified in real outcomes. It was seen in both the VG15 Eagle Complex scenario and in the subway explosion scenario at GC15. In both cases, responders continued to move through the tactical environment notwithstanding complete, or almost complete, loss of communication with tactical command and without implementing effective mitigation strategies. The only difference in the outcomes of the two teams was that VG15 moved toward an area of increased risk (into a structurally unstable building), while GC15 moved into a benign area and avoided (notional) injury.

A similar negative outcome was seen in the 2008 Squirrel's Nest Lane fire in Colerain Township, Ohio. In that event, a 15-year veteran firefighter captain and a 3-year veteran firefighter were lost in a residence fire due, in part, to loss of situational awareness and radio communications as they moved into an area of increasing risk.

Implications for Future Technologies

In recent years, the first responder community has witnessed increased attention to the need for reliable voice communications, particularly in the aftermath of the 9/11 terrorist attack and Hurricane Katrina's assault on New Orleans. This has expanded to include the need for more wideband communications technologies capable of providing services such as image transfer, video streaming and geolocation. Many new technologies are currently being developed to answer this need.

New technologies require new standards. The Association of Public Safety Communications Officials (APCO), in conjunction with Telecommunications Industries Association, has developed the wideband P34 standard for this purpose [19]. These standards and their design implementations have resulted in robust wireless systems that are resilient to fluctuations in the data transmission density. Thus, the potential is low for significant interference to arise in the future due to increased density of RF data transmission for any realistic tactical applications of wireless broadband within a personal area network.

The public safety technology sector has seen massive growth and widespread use of standard-based broadband technologies such as Wi-Fi, WiMAX and AeroMACS, as well as cellular systems (4G, 5G, LTE). The first responder community has and will continue to employ one or more of these for reasons of economy, reliability, flexibility and scalability [4]. Planners of systems to be used by first responders should weigh other characteristics as well, such as security (user credentialing) and wider coverage areas (multihop).

Further work is needed in order to continue to mitigate the risks faced by the Responders of the Future. Many new technologies are in development to help achieve this goal. These include the development of the nationwide broadband communications architecture (FirstNet), responder location and accountability systems, and physiological (biometric) status monitoring technology. The development of FirstNet will be an improvement in tactical communications for responders as long as cellular connectivity is good. A nationwide interoperability standard, with the application of portable communications technology needed to support it, will make multi-agency communications easier to set up and will have less chance of failure due to technical mistakes.

However, failures in connectivity, such as in a subway or other impoverished UHF signal environment, will necessitate use of an alternative technology or set of technologies. As has been documented through this research, disruption or degradation of RF signals can be expected based on the types of environments within which communications is required. So, for example, a responder using an 800 MHz portable radio in simplex mode to talk to another of the same model is likely to experience significant loss of communications within a metal warehouse. When responders face these types of situations, recognizing the potential for RF loss and having alternative or augmentative technologies to mitigate the loss can be crucial to avoiding high-risk situations.

Some environments will not support RF transmissions of any frequency. In such cases, augmenting the signals with portable wireless repeaters might be a useful mitigation strategy. Such wireless repeaters, supporting cellular as well as other first responder transmissions, could be dropped as first responders enter areas where signal loss is expected or found so tactical and status communications can be maintained. The researchers conceptualize this type of system as "breadcrumbs" that first responders can easily deploy. All of the smartphone-based technologies for accountability, location and physiological monitoring can also be supported by augmenting cellular connectivity in this way.

A key support for making the breadcrumbs technology feasible is the ability for first responders to recognize the loss of RF connectivity as it happens. Current portable communication devices only signal connectivity loss when keyed up by the first responder. Modifying hand-held radios to continually monitor connectivity would improve the situational awareness of the first responders and offer an early opportunity to mitigate potential risks.

Although it is attractive to consider adding more interactive wireless technology to the suite of equipment carried by first responders, the effect on the workload of people within the tactical envelope should be of paramount consideration. As was clear from the workload analysis results, cognitive and physical workload was moderate to high when the participants were burdened only with portable radios. The addition of devices that draw from visual or processing attention channels could be counterproductive, and possibly dangerous. Modifications to existing devices that reduce cognitive load, such as verbal status prompts from radios rather than signal tones that must be interpreted, could help mitigate some of the problems seen during the exercise scenarios.

If it is invisible to the tactical first responder, the addition of physical status or location monitoring technology to the suite of equipment available for the tactical commander might offer great benefit for reducing risk and increasing situational awareness. Current accountability techniques are dependent on timely and frequent radio communications, dedicated accountability officers and old-fashioned whiteboards. These are all potential points of failure. However, a wireless system to replace that function that was subject to limitations in signal strength would present a single point of failure, and would thus be of limited use in actual implementation. Mitigating the loss of signal strength using breadcrumbs technology could make advanced accountability systems feasible.

Improvements to Methods and Tactics

In the exercises observed during this research, frequency planning was properly accomplished to limit interference from the various transmitters on-scene. The researchers expect planned frequency assignment execution to be an important component of ensuring and assuring first responder communications in any real-world emergency response. However, there was evidence of minimal preparation when it came to radio choice, antenna placement, antenna gain, proper vehicle shielding and ground plane. First responders simply used the equipment that they had at hand, jumped out of the truck and went at it.

At the VG15 Eagle Electric Complex, the researchers were able to monitor all communications clearly because they used a quality antenna mounted at a proper elevation on the roof of the data collection vehicle. The incident commander was not able to hear radio traffic consistently from his tactical teams because communications from his mobile command vehicle, a metal trailer, relied on the use of portable radios. The addition of mobile radios, with roof-mounted antennas on the command vehicle, would have greatly expanded the communication range.

- It is recommended that mobile command vehicles and other tactical support apparatus be equipped with mobile radios having well-mounted, high-quality antennas with a good ground plane.

Responders in VG15 Eagle Complex and in GC15 subway scenarios both exhibited the tendency to move forward without clear communications.

- It is recommended that responders get regular training on understanding the alert tones from their radios.
- It is recommended that responders use standardized speech to effect clear communications.
- It is recommended that responders obtain regular training on the importance of restoring lost communications before proceeding into tactical environments.
- It is recommended that radios provide better discrimination among causes of communication loss, i.e., between transmission failure due to signal loss versus low-battery condition or busy channel.

Issues and Challenges for Future Communication System Development

The future development of mobile communication systems for public safety applications will expand the use of available frequency spectra. It is difficult to know exactly how much spectrum is available and allocated for public safety applications because the FCC allows all bands that are allocated for mobile communications to be used for any mobile application including public safety communications.

According to one FCC document published in 2010, 97 MHz of spectral bands are allocated for PS applications, "Public safety has a total of 97 MHz of spectrum allocated for use across the RF spectrum with 60 MHz of that total available for broadband use. Overall, the allocation of spectrum per user for public safety is now 25 times that of commercial providers." [20].

However, it is certain at this point that the following spectra are currently allocated for public safety communications:

- VHF Low Band: 25-50 MHz of which 6.3 MHz allocated for PSC.
- VHF High Band: 138-144 MHz/ 148-174 MHz of which 3.6 MHz allocated to PSC.
- UHF Band: 450-460 MHz; 10 MHz of bandwidth of which 3.7 MHz allocated to PSC.
- 700 MHz Band: 758-775 MHz and 788-805 MHz; a total of 34 MHz bandwidth, 2 MHz allocated for guard band.
- 800 MHz Band: 806-815 and 851-860 MHz; a total of 16 MHz bandwidth.
- 4.9 GHz C-Band: 4.94-4.99 GHz; 50 MHz of bandwidth.

This is a total of 111.6 MHz of allocated spectrum to public safety communications. This excludes the T-Band, 800 MHz Band Extension and Guard bands, and the 700 MHz guard band. It appears there are significantly more spectra available to be used for public safety applications than some FCC documents show.

Several issues need to be kept in mind vis-à-vis mission critical communications with regards to public safety, especially in the event of a large-scale natural disaster or extensive manmade catastrophe.

- The capability to exchange information through mobile radio, with an adequate network capacity and capabilities, is a key component of emergency response to natural and manmade disasters. Efficiency, cost-effectiveness, technical feasibility and reliability must be taken into account when planning, establishing and selecting a communication technology for public safety.
- A critical problem, particularly when a large-scale natural disaster has occurred, is that different first responders and public safety agents may use different information transmission technologies that are often not interoperable. Therefore, interoperability is an issue that continues to need resolution.

- In critical situations, PS wireless networks rapidly become congested.
- During a disaster period, public telecommunication networks, such as cellular phone networks, become congested as well, to the extent that they become unavailable.
- Although licensed frequencies are typically not subject to co-location interference, RF interference of different sorts, particularly signal path losses, continues to be a challenge for PS communications systems.
- The need for broadband systems that are capable of high-speed transmission of data, images, video and voice has become apparent. This problem has been partially addressed by the FCC's allocation of bands over 700 MHz Band and 4.9 GHz Band for broadband PS communications.
- Some have argued that the current systems that are based on mobile base stations are inadequate to meet the needs of mission critical communications. They further argue that current mobile networks lack disaster recovery and congestion control mechanisms that allow the system to work even in case of a failure of key backhaul network links. Instead, they propose a private mobile network based on LTE cellular technology that can provide an efficient IP connectivity during emergency situations [21]. This is the basis for FirstNet.

The critical issues facing the development of future radio communications systems, such as FirstNet, are the need to:

- Enhance interoperability;
- Offer adequate network capacity and capabilities;
- Provide broadband connectivity; and
- Cope with traffic congestion and RF interference in the event of an emergency situation.

RECOMMENDATIONS

- Planners of wide-band systems to be used by first responders should weigh characteristics such as security (user credentialing) and wider coverage areas (multihop).
- Develop a system of standard scenario templates and automated tools for placement of repeater stations to preserve line of sight communications.
    - The researchers have conceived this as a system of "breadcrumbs" consisting of repeaters that are laid down by, or autonomously follow, first responders during ingress into a structure to preserve line-of-sight communications.
- Develop methods to enable tactical team members to identify when radio communication loss occurs to minimize the impact to operations.
- Develop a risk mitigation decision template for addressing loss of radio communications. This work needs to include the development of training with alpha and beta testing on its use to enhance the safety of first responders.

FUTURE RESEARCH

The results of the current research illustrate the challenges to mission critical communications faced by first responders, now and in the foreseeable future. The complexity of factors that impact the loss of RF signals in various environments presents a challenge to first responders as they try to maintain radio communications within the wide variety of environments they face.

- Research RF signal loss and degradation in urban and absorptive environments and make recommendations for anticipating and mitigating problem areas.
- Research the potential for high levels of technology dependence in incident command to prevent new single point of failure risks when technology fails. Develop methods to mitigate this risk.

- Research and develop a prototype autonomous repeater swarm system (ground or air based) to follow first responders into a hazardous environments to maintain radio and PAN communications links in absorptive environments.

Cognitive load, coupled with infrequent experience with the signaling tones from portable radios in both VG15 and GC15, impacted the ability of first responders to identify the causes of radio communication loss and then mitigate that loss.

- Research the impact of 'battle rhythms' in the first responder tactical environment and investigate methods to recognize loss of situational awareness and cognitive overload in incident command.
- Use previous research on cognitive workload in military operations to design and conduct a research program to investigate cognitive workload on first responders.

CONCLUSION

MERC has been honored to partner with the DHS S&T team to conduct research on first responder electronic safety equipment and RF interference associated with wireless devices. Our partnership with DHS provided the necessary credentials to participate in national-level exercises, such as Vigilant Guard 2015 and the annual Hartsfield-Jackson International Airport aircraft fire rescue exercise. These national exercises, coupled with Guardian Center and smaller scale exercises, provided a robust data set to satisfy DHS research objectives. It is our hope that by conducting this research we can improve first responder safety, mission effectiveness and identify opportunities to reduce risk for future operations.

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