


# First Responders Group

## A Review of Satellite Communications and Complementary Approaches to Support Distributed Disaster Response

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# A Review of Satellite Communications and Complementary Approaches to Support Distributed Disaster Response

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# EXECUTIVE SUMMARY

It is well documented that Internet communications during incident and disaster response are often insufficient, which presents significant issues for first responders. The importance of reliable information and communication technologies (ICT) has been repeatedly demonstrated by Hurricanes Katrina and Sandy, the Deepwater Horizon Oil Spill, and numerous other events. There is generally a reliance on terrestrial infrastructure, which is particularly susceptible to natural and man-made events or may not exist in remote locations. While there are numerous existing approaches and platforms to provide rapidly-deployable communication capabilities, the landscape is often ill understood due to its size, breadth, rate of change, and budget constraints.

Satellite communications (SatCom) in particular can provide near instant voice and data connectivity, and commercially-available SatCom options, such as the Broadband Global Area Network (BGAN) or Very Small Aperture Terminal (VSAT), can be rapidly deployed to provide connectivity to support a range of needs, from a single user accessing e-mail to a small command center. The unique capabilities of satellites are well suited to fill certain gaps in communications during disaster response. In a disaster-affected area, a satellite may be the only mode of communication due to a lack of or degraded infrastructure. However, traditional networking protocols struggle to make efficient use of satellite capacity. There is no "silver bullet" to provide connectivity, and successful implementations are often scenario-specific involving hybrid solutions.

This study covers:

- The elements of ICT
- A survey of SatCom technology
- Hardware and software solutions for extending the ground range of SatCom connectivity to mitigate the effects of limited bandwidth
- Evaluations of SatCom performance utilizing the U.S. Department of Homeland Security Science and Technology Directorate First Responders Group's Next-Generation Incident Command System in various configurations
- Emerging and experimental technologies to complement satellite connectivity, including small unmanned aircraft systems and the new, enhanced public safety frequency allocations
- Recommendations and best practices for users

The importance of both hardware and software approaches are considered. From a hardware perspective, key aspects include portability, durability, standards-based connectivity, ease of use, and the power source. The implications of relying heavily on propriety or single-use systems are also discussed. Similarly, software that requires high bandwidth, significant processing power, frequent updates, or special skills is not ideal for use in an emergency in which communications exist but have been compromised. Software tends to take advantage of ever-increasing available bandwidth, and the same software practices that make programs appealing (e.g., polished user interfaces, robustness, instantaneous update rates, large sets of nice-to-have features) can make them nearly unusable when bandwidth is limited. Additionally, many SatCom data subscriptions are rated by the amount of data sent/received, making unnecessary data transmission undesirable. Both hardware and software approaches also face the same overarching challenge: to provide capability at a reasonable cost.

Given that there is no silver bullet to communication issues, it can be advantageous to consider complementary approaches to mitigate reliance on SatCom solutions. Under catastrophic conditions, the Federal Communications Commission identified unmanned aerial systems, aerostats, and deployable "suitcase" systems as candidate deployable communication technologies to extend or create networks to address this capability gap, which can also interoperate with SatCom systems.

## BGAN AND VSAT SATCOM COMPARISON

When purchasing equipment for emergency data communications, it is important to understand that the majority of the expense is due to data access, though more clearly so for BGAN than for VSAT. VSAT satellite dishes involve a relatively large upfront cost and are generally not hand-portable, but the data rates are high and the data plans are fairly reasonable. The VSAT data plan chosen for this study supported 2048 kilobyte (KB) download and 768 KB upload; the cost of the data plan was $599 a month for 5 gigabytes and $0.15 for each additional megabyte. The plan can be purchased for approximately $30,000, though similar systems that require more advanced expertise to operate can be purchased for as little as $3,000.

BGAN terminals are relatively inexpensive to purchase, support both data and voice communications, are lightweight and portable, and are extremely easy to set up. Costs generally range from $1,500 to $5,000 for stationary devices and $5,000 to $15,000 for vehicle-mounted devices that can be used while in motion. Typical bandwidth capabilities range from ~0.38 megabits per second (Mbps) download and ~0.25 Mbps upload at the low end to a maximum of ~0.5 Mbps for both upload and download. BGAN terminals transmit on a frequency that offers the ability to utilize small portable terminals and has good weather penetration. The major disadvantage is that both the terminals and the satellites used for BGAN communications have a lower bandwidth and therefore a lower effective data rate.

## MINIMIZING BANDWIDTH

In order to minimize costs, managing data effectively and eliminating unnecessary data usage is of utmost importance. Some data providers have data usage reduction software that utilizes compression and resampling techniques to reduce the amount of data transmitted. In addition, some programs allow the user to strip Web pages of ads or other nonessential information.

Best practices for minimizing general bandwidth usage over a satellite link include:

- Turn off automatic updating for all possible programs (e.g., Microsoft, Adobe, Java, most anti-virus programs) to ensure that these programs do not consume unnecessary bandwidth.
- Install a firewall application (one is included with Windows 7 and above; Zone Alarm is a well-reviewed third-party application) that will inform users of programs that are accessing the Internet and block ones that are not vital.
- Minimize use of auto-refreshing websites.
- Disable automatic loading of images or videos when possible (e.g., in e-mail clients, certain webpages).
- Compress files and images whenever possible before transferring (e.g., by e-mail).
- Install bandwidth monitoring software.

Ensuring reliable, efficient, and timely communication during a disaster and the ensuing response is an incredibly difficult problem with no single answer. However, when terrestrial infrastructure is damaged or unavailable, there are several reliable SatCom solutions available. These solutions introduce their own challenges, such as cost, but there are both hardware and software solutions available to help maximize the efficient use of the bandwidth available, thereby improving communications and minimizing the overall cost. Furthermore, upfront care and consideration by first responders regarding the interoperability of hardware and software can greatly reduce the communication challenges faced when a large-scale disaster occurs.

# 1. INTRODUCTION

One of the most significant and persistent issues for first responders during incident and disaster response is ensuring that sufficient communication is available to facilitate coordination. The importance of reliable information and communication technologies (ICT) has been repeatedly demonstrated by Hurricanes Katrina and Sandy, the Deepwater Horizon Oil Spill, and local events. There is generally a reliance on terrestrial infrastructure, which is particularly susceptible to natural and man-made events. While there are numerous existing approaches and platforms to provide rapidly deployable communication capabilities, the landscape is often ill understood due to its size, breadth, rate of change, and budget constraints.

Satellite communications (SatCom) in particular can provide near instant voice and data connectivity, and commercially-available SatCom options, such as the Broadband Global Area Network (BGAN) or Very Small Aperture Terminal (VSAT), can be rapidly deployed to provide connectivity to support a range of needs—from a single user accessing e-mail to a small command center. However, as this study will discuss, there is no "silver bullet" to provide connectivity, and successful implementations are often scenario-specific involving hybrid solutions.

The goal of this study is four-fold: 1) to provide first responders and supporting entities with a primer on SatCom-related options pertaining to data connectivity (voice transmissions are generally understood and are mentioned only briefly within this study); 2) to examine methods to optimize software system performance in bandwidth-constrained environments; 3) to examine new and emerging technologies, such as the U.S. Department of Homeland Security (DHS) Science and Technology Directorate (S&T)-sponsored Small Airborne Communications Platform, to provide another layer of communications capability in disadvantaged environments; and 4) to provide recommendations for next steps related to SatCom to support distributed disaster response.

More specifically, this study will discuss:

- The elements of ICT
- A survey of SatCom technology
- Hardware and software solutions for extending the ground range of SatCom connectivity to mitigate the effects of limited bandwidth
- Evaluations of SatCom performance and utilizing the DHS S&T First Responders Group's Next-Generation Incident Command System (NICS) in various configurations

- Emerging and experimental technologies to complement satellite connectivity, including small unmanned aircraft systems (SUAS) vehicles and the new, enhanced public safety frequency allocations
- Recommendations and best practices for users

In addition, the importance of both hardware and software interoperability utilized by first responders is considered. The importance of using the same hardware and software tools that first responders use on a daily basis during response efforts in disadvantaged communication environments is also discussed. Further, as available bandwidth decreases, it becomes even more critical to ensure that essential information is shared appropriately and efficiently; this study discusses approaches to address these barriers by leveraging NICS as a pathfinder to increasing situational awareness in disadvantaged communications environments.

# 2. ELEMENTS OF FIRST RESPONDER INFORMATION COMMUNICATIONS TECHNOLOGY SYSTEM

The difficulties in affecting efficient communications for disaster response and during large-scale, rapidly-evolving events are well documented, as is the need for rapid deployment of ICT in the immediate hours following a large-scale disaster. Following Hurricane Katrina, a bipartisan U.S. House of Representatives committee published a report in 2006 entitled *A Failure of Initiative: Final Report of the Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina* [1] that specifically identified that the response "*lacked needed communications equipment and interoperability required for seamless on-the-ground coordination.*"

The emergency response community has been hampered by an inability to share timely data; a lack of shared situational awareness; duplication and/or staleness of relevant information; and key data shared in inaccessible formats, among other difficulties related to sharing or accessing needed information. Some approaches to address these communication and interoperability problems include:

- Establishing communication links
- Identifying and mitigating barriers to information sharing
- Creating and promoting data sharing services
- Identifying and mitigating field constraints

## 2.1 ESTABLISHING COMMUNICATION LINKS

As the Internet is the primary means of interagency communication for the myriad government, civilian, and military organizations that participate in multi-organizational disaster response, it is vital that it be considered a priority when establishing multi-organizational communications. Many commercial off-the-shelf (COTS) components exist to establish field Internet connectivity as well as to extend its reach over ever-increasing geographical ranges. For example, 3G and 4G Long Term Evolution (LTE) laptop USB sticks and MiFi wireless routers can take advantage of signals from operational cell towers, or a mobile antenna tower and receiver commonly referred to as a Cell on Wheels (COW) may be employed in cases where access to cell towers is compromised. Commercial signal boosters and repeaters can increase this range. However, when infrastructure is compromised, these may not be available and the ability to establish self-contained Internet access becomes critical. VSAT, BGAN terminals, and satellite phones all utilize satellite connectivity to establish an Internet connection that is independent of local terrestrial communication infrastructure. These hardware options are discussed in detail in Section 3. Additionally, when LTE is unavailable, it becomes critical to extend the range of newly established communication points beyond the immediate area. Among other options, a series of high-performance routers may be set up in order to create a wireless mesh network (WMN) to increase Internet availability over a wide coverage area. These technologies are discussed in Section 4.

## 2.2 IDENTIFYING AND MITIGATING BARRIERS TO INFORMATION SHARING

Many barriers exist to sharing critical information in a timely manner. Some of these barriers are solely technology-based, though many are also policy/institution-based. These barriers include:

- Stovepipes or proprietary formats
- Lack of understanding as to what is available or how to access it
- Decentralized organization with no trusted way to share
- Reliance on contact lists that do not dynamically account for new personnel or organizations that require access
- Static information that does not update in real time or nearly real time
- Multiple copies of information with no clear genealogy or traceability
- Lack of funding for software/hardware/training

These barriers can be time-consuming and inconvenient during everyday events, even with the nearly unlimited bandwidth provided by terrestrial networks. However, the problems caused by inefficient data sharing can become critical during the low-bandwidth and time-critical environment created by a large-scale disaster. It is therefore important to address these concerns as part of a comprehensive communications-compromised plan.

When discussing interoperability and efficient data sharing, adhering to open standards and formats is a key criterion for success. For hardware, it is the lynchpin to establishing a network that is as low cost as possible to set up, run, and extend when required. It is even more important that internationally-recognized open standards are adhered to in software used to create or share data. For example, a propriety plume-modeling package that has the option to produce its output in a standard geographic information system (GIS) format enables a user to quickly upload that file into a system that allows other first responders almost immediate access to that information on the interactive or passive viewer of their choosing. That same package, which produces an output in a proprietary or non-standard format, can cause the information to be shared only in picture form or only for use on a proprietary viewer that is not available to many of the responders who require access to that information.

Stovepipes within organizations can cause information to be unavailable or opaque to responders in different organizations. The information shared is often at the discretion of someone who e-mails information to a previously designated list. Significant efficiency can be gained if members of each organization designate the superset of useful information they are willing and able to share and then publish that information in a clearinghouse. This enables members of other organizations to see and access all available information and pull the specific data that enables them to fulfill their mission, be it response or to support further analysis, which can also be shared with others. Again, it is important to note that this is made more effective when the programs and data formats involved adhere to open standards, ensuring that those who are accessing the information may make the best use of it.

Decentralized organization and individual organization policies can make it very difficult to share information within policy guidelines. The result is often a complete lack of information sharing or the sharing of information that is too stale to be actionable. The reliance on pre-existing or slowly modified contact lists and the real-time judgment of those on the sending or receiving end can either prevent information from getting to those who most need it or cause it to be forwarded to those who are not authorized to see it. Addressing these policy considerations is beyond the scope of this report, though software solutions are in development, such as the Virtual USA® initiative, sponsored by the DHS S&T First Responders Group, which enables organizations to quickly take advantage of the ability to share data once the data owner decides what is appropriate to share and with whom.

Static representations of dynamic situations (i.e., stale information) are another source of inefficiency. While it makes sense for certain information to be vetted before release to various organizations (i.e., press releases), oftentimes information is not released to fellow responders until it has been modified, messaged, or simply imaged and transferred to a system to be e-mailed out. It is often desirable for information to be updated in real time or nearly real time and made available on an as-needed basis. A field responder with limited bandwidth will likely want to access a current report or situational awareness map when the information is actionable and not waste time and resources downloading several hourly reports, only the last of which is relevant. In addition, it is often desirable to have transparency in the origin and genealogy of information, down to who supplied which pieces of information in a situational awareness picture. This can save time and resources when a responder wishes to determine the reliability of actionable information before committing to a course of action.

Finally, a lack of funding for first responders to purchase expensive hardware or software solutions, as well as a lack of resources to participate in training to understand how to utilize complicated or proprietary systems, makes it vital that any solutions to the above problems have a low barrier to entry. Solutions must be inexpensive and easy to access and use on currently-employed or easily-obtainable COTS devices.

## 2.3 CREATING AND PROMOTING DATA SHARING DEVICES

A lack of situational awareness and communications, as well as the absence of interoperability among the response agencies, are among the most cited factors that hamper first responders' abilities to make critical decisions [2]. To this end, it is critical that all elements involved in a response are able to effectively communicate, whether in a nominal or a communications disadvantaged environment. Figure 1 illustrates many of the elements that may be involved in a response.

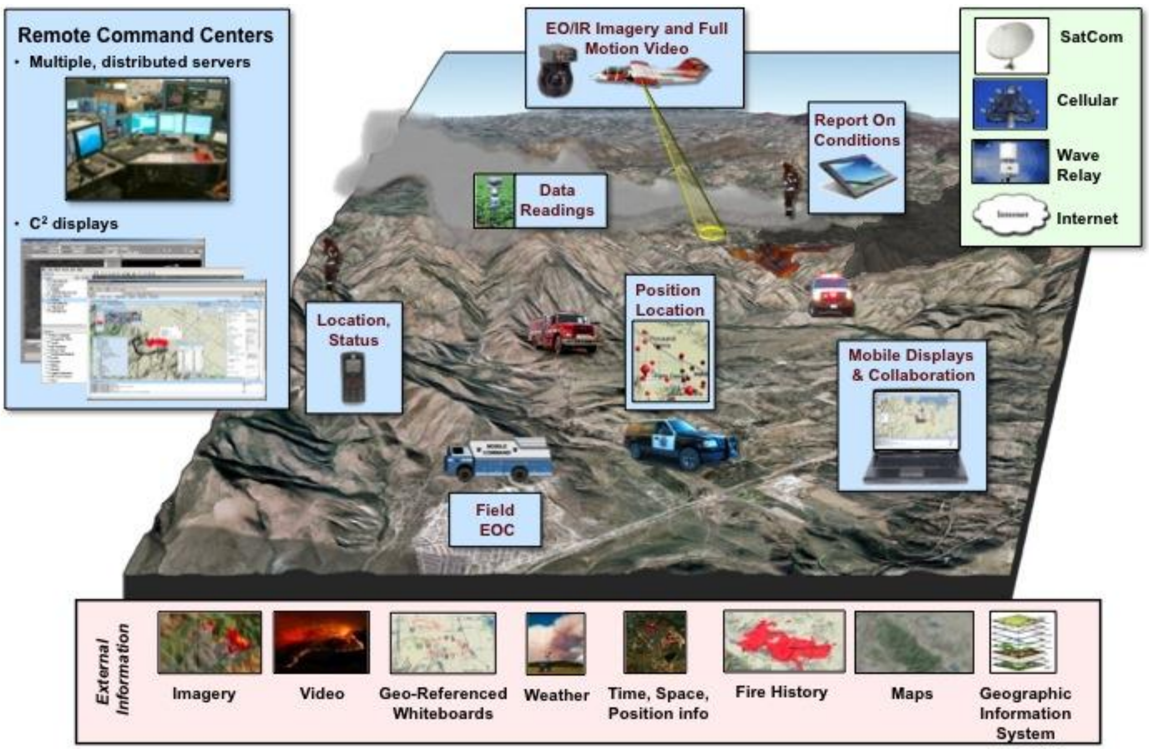



*Figure 1. Common elements in emergency response*

Devices in the field may include stand-alone sensors, simple phones, smartphones, hand-held tablets, and laptops. Ideally, these devices will be equipped to take advantage of multiple means of communication. For example, smartphones can utilize WiFi, Bluetooth, or 4G connections, and devices used by first responders may have built-in abilities to utilize WiFi, LTE, WiMax, and satellite connections or have the ability to use adapters to do so.

The ability to share and receive data will, to some extent, depend on the type of device employed. Stand-alone sensors may need only to report status and so may only have and need the ability to send data via structured text. Iridium Satellite modems work nearly anywhere in the world but have such limited bandwidth available that their data sharing is restricted almost entirely to sending and receiving text. Smartphones and smaller tablets have limited viewing areas (i.e., screens) and are not compatible with many types of software or Web applications (e.g., Flash).

In order for first responders to work effectively, they must be able to communicate efficiently and effectively with all elements of the Incident Command Structure (ICS). This includes their colleagues in the field as well as their command structure. These are often referred to as parallel communication and vertical communication, respectively.

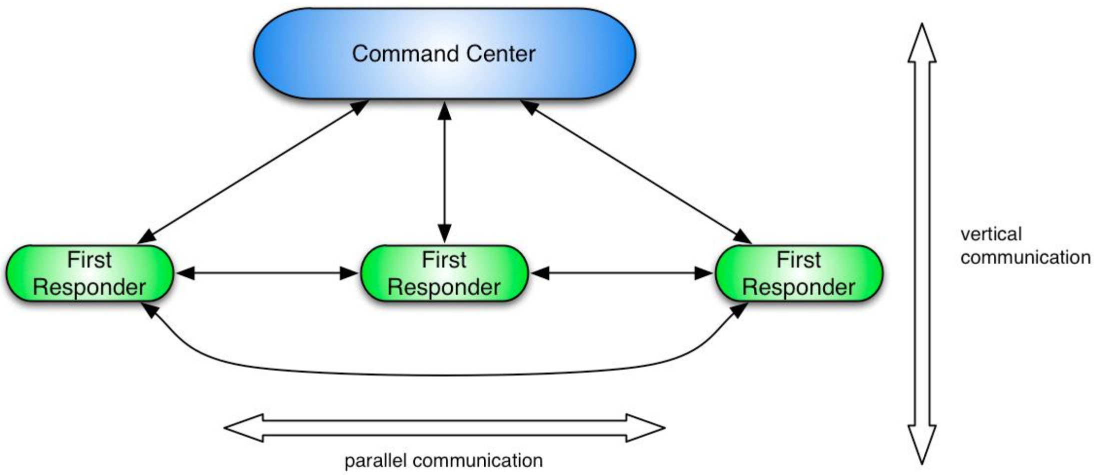



*Figure 2. Parallel and vertical communication*

However, in addition to a responder's immediate command and colleagues, it is sometimes necessary for ICS personnel to communicate with those outside their immediate structure. Information obtained by a firefighter taking radiation readings may need to be shared with the National Guardsman who is coordinating evacuations in that area, or information may need to be relayed to an expert in an unrelated organization for analysis. While the decision to share the information is governed by ICS, the share may not fall within the ICS umbrella. The American Red Cross is one example of an organization that often receives shared data during medium- to large-scale events.

Given these considerations, the value of tools and software that can easily interoperate becomes even clearer.

## 2.4 IDENTIFYING AND MITIGATING FIELD CONSTRAINTS

### Hardware

Special consideration must be given to hardware and software used in the field. James Gregory Gabriel of the Naval Postgraduate School has written a thesis exploring evaluation criteria for communications hardware under consideration for emergency ICT. The importance of environmental durability, portability, an internal power source, standards-based connectivity, and ease of use are discussed, and a method to rate ICT equipment for field personnel based on these considerations is proposed [2]. His system is intended to be applied to equipment carried by first responders in the field with little or no support, but some metrics (notably, environmental durability and standards-based connectivity) may be equally applied to equipment for a field Emergency Operations Center (EOC). A summary of his method is as follows:

### Environmental Durability

It is important that equipment used in the field can withstand typical and sometimes extraordinary weather conditions. The International Electrotechnical Commission (IEC) has defined international standard IEC 60529 [2] to specify durability standards, which are used below.

**TABLE 1**

**Evaluation Criteria for Environmental Durability [2]**

| Insufficient (value = 0) | Limited (value = 1) | Exceptional (value = 2) |
|---|---|---|
| System is not well suited for an outdoor environment. Rating does not meet Ingress Protection Rating 54 (IP54)*1 | System meets accepted standards for limited environmental durability. Rating meets or exceeds IP54*1 | System meets accepted standards for harsh environmental durability. Rating meets or exceeds IP67*2 |
| Example: System intended for home/business use. Limited outside durability. | Example: System is dust-protected and protected against water jets. | Example: System is dust-tight and protected against effects of temporary immersion in water |

*1 Dust-protected and protected against splashing water

*2 Dust-tight and protected against the effects of temporary immersion in water

### Portability

Gabriel determined that industry-standard protective cases from Pelican Products, Inc. were an appropriate guide. Pelican cases are watertight, crushproof, and dustproof and are therefore ideal for hand-carrying equipment to a field location. In addition, the Pelican 1520 and 1400 cases are appropriately sized to be carried on an airline.

*Figure 3. Pelican 1520 case*

**TABLE 2**

**Evaluation Criteria for Portability [2]**

| **Insufficient (value = 0)** | **Limited (value = 1)** | **Exceptional (value = 2)** |
|---|---|---|
| Too large and/or heavy for international commercial air carry-on baggage.<br>Weight: 15 lbs or greater<br>{or}<br>Size: > 18" x 12" x 6"<br>(L x W x D) | Small/light enough for international commercial air carry-on baggage, but too large/heavy for easy man-portability in an extreme Humanitarian Assistance and Disaster Relief (HA/DR) environments.<br>Weight: < 15 lbs<br>{and}<br>Max Size: 18" x 12" x 6"<br>(L x W x D) | Small/light enough for international commercial air carry-on baggage and easy man-portability in an extreme HA/DR environment.<br>Weight: < 7.5 lbs<br>{and}<br>Max Size: 11" x 8" x 5"<br>(L x W x D) |
| Example: Item weighs over 15 lbs or will not fit in an airline carry-on case. | Example: Item weighs less than 15 lbs and will fit in a Pelican 1520 Case. | Example: Item weighs less than 7.5 lbs and will fit in a Pelican 1400 Case. |

### Internal Power

Ideally, equipment used in the field will have an internal, easily replaced internal power source so as to be independent of local infrastructure. During recent emergencies, it has been noted time and again that information travelled by cell phone in areas where power had been out, sometimes for days. A device with a battery that can be easily replaced with a fresh one is invaluable in the hours or days it can take to get a comprehensive ICT system with generators up and functioning.

**TABLE 3**

**Evaluation Criteria for Internal Power [2]**

| Insufficient (value = 0) | Limited (value = 1) | Exceptional (value = 2) |
|---|---|---|
| Does not include any internal battery power source(s). | Includes an internal battery source, but it is intended to be removable/interchangeable. | Includes an internal, removable/interchangeable battery source. |
| Example: Device with no internal power source | Example: Internal battery not designed for field removal, requiring special tools and/or extensive labor for removal/replacement. | Example: Removing internal battery requires simple or no tools for rapid removal/replacement. |

### Standards-based Connectivity

Standards-based connectivity is vital to ensuring the interoperability of equipment in the field. The ability to quickly change out functioning equipment or to introduce new equipment is important in an office environment and even more so in the field. A working system can be foiled with the failure of a proprietary cable or the need to connect to a new piece of hardware.

**TABLE 4**

**Evaluation Criteria for Standards-based Connectivity [2]**

| Insufficient (value = 0) | Limited (value = 1) | Exceptional (value = 2) |
|---|---|---|
| Technology is a draft standard, proprietary, or limited to a particular country/organization. | An internationally recognized standard is only present for either configuration or end-users (not both). | Technology is an internationally recognized standard for both configuration and end users. |
| Example: All device communications require special, non-standard interfaces (e.g., Department of Defense only). | Example: End-users can use a technology such as WiFi (802.11a/b/g/n), but configuration requires a special, non-standard connection. | Example: Standard technology such as WiFi (802.11a/b/g/n) that is widely used. |

### Ease of Configuration

First responders cannot count on the immediate availability of personnel with special training in equipment setup and maintenance. Therefore, to a large extent, the usefulness of field equipment is dependent on the ease of setup and use.

**TABLE 5**

**Evaluation Criteria for Ease of Configuration [2]**

| Insufficient (value = 0) | Limited (value = 1) | Exceptional (value = 2) |
|---|---|---|
| System only configurable by a certified technician/engineer or requires manufacturer for configuration changes. | System requires installation of special software for configuration.<br>{or}<br>System requires additional specialized equipment for configuration | System can be configured through a built-in interface requiring no additional software or equipment. |
| Example: Typical users deployed in the field cannot reconfigure device. | Example: Configuration requires certain licensed software or equipment, such as a spectrum analyzer. | Example: System configurable through a Web browser and standard data connection. |

**Obtaining a Metric**

A quantifiable metric is obtained by simply adding the overall score for a possible total of 10. Gabriel rated a series of devices; one example, a Hughes 9201 BGAN Inmarsat Terminal, follows.

BGAN terminals are discussed in detail in Section 3. The Hughes 9201 BGAN Inmarsat Terminal has the following specifications [2]:

**Physical**

Size: (L x W x D) 13.6” x 10.8” x 2.0” (345 x 275 x 50 mm)

Weight: 6.2 lbs (2.8 kg)

**Environmental**

Ingress Protection (IP) / National Electrical Manufacturers Association (NEMA) Rating: IP 55

Operating Temperature: 13 to 140° F (–25 to 60° C)

Power External: Power 110–240 V AC (20 V DC)/Device Input: 11.1 V DC

Internal Battery: Yes

Battery Specifications: Lithium Ion, Removable, Rechargeable, 36-hour Standby

**Data Interface**

Primary User: WiFi (802.11b)

Primary Configuration: Ethernet (Institute of Electrical and Electronics Engineers [IEEE] 802.3)/RJ-45

Other: USB, Integrated Services Digital Network (ISDN)

**System Capability**

IP Data: Send/Receive Up to 492 Kbps

Voice: 4 Kbps, 3.1 kHz voice

Short Messaging Service (SMS): 160 Characters

Configuration: Interface Built-in Web Server (Optional: Inmarsat BGAN LaunchPad Software)

External Configuration: Requirements N/A


*Figure 4. Hughes 9201 BGAN Inmarsat Terminal*

Given these specifications, the device was given the following scores for each category:

Environmental Durability: 1

Portability: 1

Internal Power: 2

Standards-based Connectivity: 2

Ease of Configuration: 2

This sums to a total score of 8/10, which makes this device an excellent choice for a field first responder on foot.

As noted earlier, this system in totality is meant to rate equipment intended for a responder with little or no field support (i.e., different metrics should be applied when choosing equipment for an EOC or any site that requires access to power and large amounts of bandwidth).

**Software**

Similarly, special consideration must be given to software tools used in the field. Software that requires high bandwidth, significant processing power, frequent updates, or special skills is not ideal for use in an emergency in which communications exist but have been compromised (e.g., relying on SatCom). Software tends to take advantage of ever-increasing available bandwidth, and the same software practices that make programs appealing (e.g., polished user interfaces, robustness, instantaneous update rates, large sets of nice-to-have features) can make them nearly unusable when bandwidth is limited. Additionally, many SatCom data subscriptions are rated by the amount of data sent/received, making unnecessary data transmission undesirable.

Finally, communication delays inherent in SatCom as well as high bit error rates can wreak havock on software that relies on Transmission Control Protocol/Internet Protocol (TCP/IP) communication protocol [3]. Unlike User Datagram Protocol (UDP/IP), which sends information in packets (64 kilobyte [KB] max size) with no guarantees of delivery nor packet ordering by the receiver, the TCP/IP protocol guarantees reliable data delivery from the sender to the receiver in the order that it was sent. The guarantee of reliable delivery is of central importance to Web programs that require back-and-forth communications between a server and a Web browser. UDP could be used, for example, when broadcasting global positioning system (GPS) data to a server, since one dropped UDP packet wouldn't be disastrous in that case. On the other hand, in a banking application, acknowledgment of transactions is of the utmost importance and would require the guarantee provided by TCP/IP. While TCP/IP enables reliable back-and-forth communication, there can be significant performance issues related to the end-to-end link latency and the average link bandwidth utilization. Satellite link latency added to delays caused by routers, switches, and signal processing, which can result in significant performance degradation. Most common algorithms used in TCP/IP driver software, both on the sender and receiver side, ensure the quality-of-service guarantees of the TCP/IP protocol [3] by informing the sender to retransmit data that is perceived to have been lost. From the algorithm's perspective, high link latencies look like data loss, resulting in resending data. There is a "runaway" scenario that occurs when the volume of resent data causes collision errors on the network, triggering resending data, which causes more collisions. As a general rule of thumb, standard TCP/IP transmission on low-latency links can achieve only 60 percent network utilization; high latency links can expect to perform much worse. Devices such as performance-enhancing proxies (PEPs) can mitigate much of the degradation but are more common on large bandwidth SatCom devices than on ones with smaller throughput. PEPs are discussed in detail in Section 3.

# 3. HARDWARE

## 3.1 OVERVIEW OF SATELLITE COMMUNICATIONS

SatCom systems are a critical part of many telecommunication strategies. The unique capabilities of satellites are well suited to fill certain gaps in communications during disaster response. In a disaster-affected area, a satellite may be the only mode of communication due to a lack of or degraded infrastructure.

Satellite coverage is available virtually all over the Earth's surface. It can be used to temporarily alleviate congestion on existing infrastructure or provide a network where infrastructure does not exist. Finally, SatCom can be quickly provisioned where building, repairing, or growing other systems would take considerable time.

The specific use case will help select the appropriate technology and may also place significant constraints on what should be deployed. For example, for a fixed terminal where the participant in the network is not mobile, users may be able to afford larger terminals. This broadens the choice of available satellites, and higher bi-directional data rates may be available if all parties are stationary (i.e., fixed-to-fixed). Finally, this opens up the possibility of building networks for multiple users at each ground station.

On the other hand, if participants are moving—by air, ground, or sea—this places significant restrictions on the size of the terminal, which restricts available satellite systems and data rates.

A basic satellite system includes a space segment that provides services to a specific ground segment. The design of each segment depends on the type of service being provided—fixed, mobile, or direct broadcast (like satellite television). Each satellite has a coverage region, and communication can be established between all Earth stations located within a single coverage region.

Satellite services are conceptually divided into the following three categories:

- Fixed Satellite Services (FSS) provide links between terminals at fixed locations on Earth.
- Mobile Satellite Services (MSS) provide links from or to mobile terminals.
- Broadcast Satellite Services (BSS) broadcast to multiple receiving stations.

FSSs have a wide range of Earth stations, the size and characteristics of which depend on the user being supported. An Earth station handling international traffic may have antennas as large as 30 meters (m) diameter with significant hardware and software complexity. On the other hand, an Earth station supporting customers directly may be as small as 1 m diameter, with simple hardware for radio frequency (RF) and baseband. The interface from the station to the end user may involve either the public switched network, or another local/regional network.

The ground segment of MSS varies based on the nature of the station. For example, an airborne terminal will have different restrictions when compared to a personal communicator with respect to size, cost, and environmental impact.

While SatCom systems are complex, in this report we will focus on the aspects of the systems that are of interest when selecting and deploying the right technology.

### 3.1.1 Orbits

An orbit is a periodically repeated path traced by a moving body. For this report, we will limit our discussion to low Earth orbits (LEOs), medium Earth orbits (MEOs), and geostationary Earth orbits (GEOs).

A GEO satellite is placed at an altitude of approximately 35,786 kilometers (km) with a velocity in orbit of 3075 m/second (s) with a circular, equatorial orbit. This causes the satellite to appear stationary to an observer on the ground. The advantages of such an orbit are significant for communications, because this satellite is continuously available at all times for a region on the ground. The tracking requirements for the terminals are minimal and parameters such as path loss will not change. In addition, this orbit provides adequate coverage to the most populous regions of the Earth.

The disadvantages of GEOs include a significant delay (~250 milliseconds) and the occasional (but predictable) degradation due to solar interference. Also, if coverage is required in areas beyond ±76° latitude, a GEO satellite may not be sufficient due to the low elevation angles. Typically, GEO SatCom operate in the high frequency bands (e.g., S-, L-, Ku-, and Ka-bands), which is worse for signal path loss. Inmarsat is an example of a commercial GEO satellite service provider.

Satellites in the LEO circle the Earth at a height of 160 to 500 km above the surface of the Earth. MEO satellites orbit at a distance of approximately 10,000 to 20,000 km above the surface of the Earth. This relatively close distance to the Earth leads to much shorter orbital periods and much smaller propagation delays. This makes LEO better suited for real-time communication applications. For example, the lower delay significantly improves voice quality as well as bandwidth utilization. LEO satellites, however, do not appear stationary to an Earth terminal. Each satellite is only visible for 10 to 20 minutes each pass. LEO systems need to frequently hand over connections from one satellite beam to another or from one satellite to another. Hence, far more LEO and MEO satellites are required to cover the earth than GEO orbiting satellites, and a network of satellites is generally required to provide continuous communications connectivity. As an example, the Iridium system uses 66 LEO satellites in a distributed architecture. MEO satellite systems are visible for longer periods, typically two to eight hours, and have larger coverage areas than LEO satellites; hence a smaller constellation of satellites than LEO is required to provide full coverage.

### 3.1.2 Topology

The arrangement of various elements on the satellite network is known as the topology. The requirements of a mission may drive the use of certain topologies. On the other hand, a user may be constrained to certain topologies based on the available equipment and service in a crisis.

#### Star Topology

In a star network topology, a hub Earth station connects to each remote site. If two remote sites need to communicate with each other, their communications pass through the hub. Smaller, low-powered upconverters can be used at each remote site, but there are additional hops of delay between remote sites. If the end user expects most communication to be between the hub (e.g., emergency response headquarters) and remote sites, then this is a good topology choice.

#### Mesh Topology

A mesh network topology allows each remote site to communicate directly with any other remote site without routing the traffic through a hub, thereby minimizing delays. This topology is preferred for real-time applications that are sensitive to delay, such as voice and video conferencing.

Both *hybrid* (a combination of different topologies) and dedicated *point-to-point* topologies (a direct connection between two and only two locations) are also often used.

### 3.1.3 Frequency Allocation

The RF spectrum is a limited resource. In the modern technology landscape, there are far more transmitters attempting to make use of the spectrum than there are discrete frequencies. Fortunately, geographic discrimination (the ability to reuse frequency due to geographically separated beams), as well as polarization discrimination, allow frequency reuse.

To avoid users interfering with each other, the International Telecommunications Union has allocated different blocks of frequencies to different purposes. Some bands of frequencies have been allocated for use for satellites, and even within these bands, there is a further division based on the type of satellite service. However, in modern SatCom, these distinctions are becoming blurry, especially with the advent of VSATs, which will be discussed later.

The frequency band may govern the size of the antenna because a higher frequency implies that a higher gain can be achieved with a small antenna. Higher frequency bands offer higher bandwidth but suffer from severe rain-induced attenuation at frequencies over 10 gigahertz (GHz). On the other hand, the range between 3 to 10 GHz suffers the least atmospheric attenuation and thus is often a preferred range for SatCom.

**TABLE 6**

**Frequency Range for Commercial SatCom**

| | Frequency Range for Commercial SatCom | Type of Service | Example Providers |
|---|---|---|---|
| **L-band** | 1.5–1.7 GHz | MSS Voice and Limited Data | Inmarsat, Iridium |
| **S-band** | 2.0–2.7 GHz | MSS, Digital Audio | Sirius XM |
| **C-band** | 3.4–7.1 GHz | FSS Voice, Data, and Backhauling | Intelsat, Satellite TV |
| **X-band** | 7.25–8.4 GHz | Military/Satellite Imagery | XTAR, Paradigm |
| **Ku-band** | 10.7–14.5 GHz | FSS and BSS | Intelsat, Eutelsat |
| **Ka-band** | 17.7–21.2 GHz and 27.5-31 GHz | FSS Broadband and Inter-satellite Links | Inmarsat, Hughes, ViaSat |

### 3.1.4 Modulation and Coding

While a detailed discussion of the topic of modulation is outside the scope of this report, we would like to highlight that the modulation scheme in use in a satellite system places constraints on the ground terminal design, and consequently its users. Certain modulation schemes are able to provide high data rates, while others are robust against signal disturbances such as propagation effects, noise, and interference. A more complex modulation scheme may require a large ground terminal.

In many cases, satellite providers choose a simple but robust modulation scheme (e.g., binary phase-shift keying or quantum phase-shift keying) to reduce power consumption and receiver complexity and use a technique called coding to provide protection against noise. Coding is a process of protecting a signal against corruption. This is achieved by adding redundant bits within the digital signal. If any bits are lost due to noise, the original data can be reconstructed using the redundant bits. There are a large number of coding techniques, many of which are complex. Satellite system designers gain a complete understanding of their channel characteristics before deciding which coding scheme will be appropriate to combat degradation.

### 3.1.5 Propagation

The channel between Earth stations and the satellite affects the propagation of radio waves. There are both natural as well as man-made factors that are considered. For example, atmospheric absorption, absorption and scattering due to clouds, fog, precipitation, and other effects contribute to the degradation of the signal during propagation.

In the range of frequencies that are in use for SatCom—~100 megahertz (MHz) to 30 GHz—C- and X-band are least affected by these effects. Ionospheric effects are mostly confined under ~3 GHz and the absorption in the troposphere becomes significant above 10 GHz.

Mobile SatCom is an even more challenging problem in the face of such impairments. Because the terminal is in motion, the path between the terminal and satellite varies continuously.

Losses due to rain fade, the absorption of an RF signal by rain, snow, or ice are especially prevalent in Ku- and Ka-band VSATs, as discussed below.

## 3.2 APPLICATIONS OF SATELLITE COMMUNICATIONS

There are numerous types of SatCom systems, each with their own advantages and disadvantages. This report will examine a few specific types of terminals and how they are applicable to the first responder community. These terminal types range in size, complexity, data rate, and costs. In the end, the community may find a collection of a few of these types of terminals to be the best solution to meet the different and unique mission needs.

### 3.2.1 Satellite Phone

A satellite phone is a type of mobile phone that provides services similar to modern cellular phones such as voice, SMS, and low-bandwidth Internet access.

Satellite phone performance and features depend heavily on the orbit of the satellite that is being accessed. For example, Inmarsat and SkyTerra use Geosynchronous satellites to provide voice and data services. As discussed earlier, this leads to longer delays (~250 ms), which are especially noticeable in voice communications. Also, they are only available at highly-populated latitudes. The available data rates range from 60 to 512 Kbps.

On Inmarsat, for example, all calls to a terrestrial network are routed via the satellite to a gateway, from where they are sent to the public switched network. The mobile links use a 1.6 GHz uplink and 1.5 GHz downlink. The satellite gateway links (feeders) use a 6 GHz uplink and a 4 GHz downlink.

On phones using LEO satellites, there is worldwide coverage without any gaps. Depending on the location and relative positions of the terminal and satellite, a usable pass of an LEO satellite may be as little as four minutes. Services such as Globalstar and Iridium overcome this by having a large constellation of satellites (e.g., Iridium has 66 satellites). The LEO satellite has a lower delay. Also, with LEO systems, even if a terminal is blocked, there is an opportunity to wait a few minutes for another satellite to pass by.

On Iridium, the mobile links to the satellite operate in the L-band in ranges of 1.616 to 1.625 GHz. To avoid interference between the uplink and downlink, they are not done simultaneously. The feeder links operate in Ka-band, with 27.5 to 30 GHz uplinks and 18.8 to 20.2 GHz downlinks. If a destination phone is on the terrestrial network, the original satellite will send the call to the nearest gateway for transmission through the public-switched network. If the call is for another Iridium user, it travels over inter-satellite links (ISLs) to the user's home gateway to determine the destination location.

Iridium advertises a data rate of up to 10 Kbps, but this is achieved through compression of data. Data rates are in the 2400 bit/s range for compressed data. While this is a very low data rate, it can be used as a reliable backup link for chat-type services when all other services are unavailable.

Globalstar is similar to Iridium but has fewer satellites (48) and does not have ISLs.

Modern satellite phones are available in sizes similar to cellular phones, as well as the traditional "bag phone" configuration with an integrated speaker, battery backup, and ruggedized case. Some phones also provide a USB or other serial connection in order to use data service as well as the ability to create WiFi hotspots.

The cost of satellite phones can be as low as $300 for a used phone to $2000 for a new, full-featured phone. Also, there is significant variability in prices based on the current calling costs and performance for a system.

Rates for voice calls made from a satellite phone can range from as low as $0.20/min with long-term contracts to $2/min for minutes used outside a plan. SMS rates are around $0.50/message. Voice calls made from mobile or terrestrial phones to a satellite phone are often significantly more expensive. The service is sold with subscriber identity module (SIM) cards, similar to cellular networks, with voice and data plans available in both prepaid as well as post-paid contracts.

### 3.2.2 Data Communications

In this section, we will discuss a few different types of terminals that are used for data communications, but also support voice and short messaging.

BGAN is an L-band service offered by Inmarsat. VSATs were originally developed for C-band, followed by Ku-band VSATs. Ka-band VSATs are a more recent development, but they promise an improved performance for the cost.

**BGANs**

BGANs are a class of terminals that uses three geosynchronous satellites operating at 1.525 to 1.559 GHz, which allows them to cover the entire Earth, with the exception of polar regions.

The BGAN service is offered by Inmarsat on their I-4 constellation of satellites. The system provides each user, at most, 492 Kbps of throughput. In addition to IP data, BGAN also provides a streaming IP data service, a circuit-switched telephone service, and a text messaging service.

The cost per bit ratio is relatively high and can range from roughly $3/megabyte (MB) to $7/MB depending on the plan and contract. As with all satellite systems, a clear, unobstructed view of the satellite is required to operate. The system is relatively robust to external weather conditions.

Since the BGAN technology is fairly mature, there are a plethora of different terminals available. The smallest terminal is the size of a modern laptop and takes approximately two minutes to set up, with a minimal amount of training. There are also vehicle-mounted solutions that can work while in motion but are susceptible to natural blockages (e.g., trees, buildings, mountains, etc.). The terminal costs are significantly lower than Ku-band and Ka-band terminals and the terminal is easier to operate. The terminals range from ~$1,500 for a small portable terminal to ~$18,000 for a larger, vehicle-mounted system.

Terminals are available from Hughes Network Systems, Thrane & Thrane Glocom, and Addvalue Technologies. The different classes of terminals also vary in the available data rates and ruggedness of design to protect terminals from weather and environmental conditions. Also, certain terminals provide Wireless Local Area Network (WLAN) 802.11 g, Bluetooth, Ethernet, and USB interfaces to connect a network of users or standard registered jack—RJ11—for voice.

One of the major drawbacks of the BGAN service is that the modems do not offer any built-in PEP functions. Due to the delays in geosynchronous satellites, TCP performance is especially degraded. As such, TCP/IP traffic over BGANs is notoriously slow. In one test performed by the Massachusetts Institute of Technology (MIT) Lincoln Laboratory (LL), TCP/IP traffic was able to achieve only 20 Kbps, whereas UDP/IP traffic was able to achieve close to 400 Kbps. External PEPs are available but require that they sit on both sides of the link, and all TCP/IP traffic needs to be aggregated through them.

***VSATs***

A VSAT network typically consists of a large Earth station, often referred to as a teleport, with hub equipment that can be connected to the Public Switch Telephone Network (PSTN) or Internet backbone. Another device may also convert the satellite protocols to IP in order to connect to a Local Area Network (LAN). At the remote site, the small VSAT antennas provide a connection for a router or have a built-in router in order to receive an IP transmission from the hub and convert it for applications like Internet, voice, and data. VSATs can be operated in any topology (star, mesh, hybrid) based on the requirements of the user.

***Ku-band VSATs***

Ku-band VSATs were first developed in the 1980s for oil drilling and exploration sites. Ku-band SatCom is a fairly mature technology and as such has reached near worldwide availability. Ku-band VSATs make up a large portion of the ground sites in use for communications today. Ku-band VSATs are a class of terminal that uses geosynchronous satellites operating at 10.95 to 12.75 GHz and 14.0 to 14.5 GHz.

Ku-band satellites are typically transponded, and in the United States, most have 36 MHz or 72 MHz of bandwidth. In the VSAT configuration the bandwidth is shared among a large group of users with typical data rates of around 0.5 to 4 Mbps. Higher data rates are possible but are usually cost-prohibitive. As with all satellite systems, a clear, unobstructed view of the satellite is required to operate. Ku-band has some susceptibility to rain fades (i.e., loss of signal strength due to rain), but most systems are designed to operate in even the most severe of conditions.

Appropriate terminals for the first responder community would include a 1.2 m (4 foot) satellite dish, positioner, satellite modem, and typically a small-scale network router (often built into the modem). Truck-mounted and transit-case-deployed systems are widely available and are reasonably priced from numerous vendors. The terminals are designed to be mostly automated, but do take a certain amount of training to operate and ensure proper positioning. Depending on the service agreement and support contract, the user may be required to phone the service provider when activating the system. This would require either access to a terrestrial phone network or satellite phone.

The National Guard Joint Incident Site Communications Capability (JISCC) incorporates a 1.2 m Ku-band satellite terminal for its broadband data requirements. The JISCC system requires the user to place a phone call to the service provider to initiate service. This requirement/limitation is one of the biggest drawbacks to the system as far as first responder use in either remote locations or in locations where the terrestrial infrastructure has collapsed.

***Ka-band VSATs***

In the 1990s, the National Aeronautics and Space Administration successfully demonstrated that the Ka-band could be used for a high data-rate SatCom system. Ka-band VSATs are a class of terminal that uses geosynchronous satellites operating at 19.2-20.2 GHz and 29.0 to 30.0 GHz. Ka-band SatCom is an emerging technology, but there are services that provide complete coverage to the continental United States.

Ka-band satellites are typically transponded, and in the United States, most have between 16 and 64 MHz of bandwidth (bandwidths of up to 800 MHz exist but are typically reserved for high-end and/or Department of Defense applications). Though the bandwidth of each transponder is, on average, smaller than Ku-band transponders, the footprint of each transponder is dramatically smaller. This allows for a higher density of transponders to cover a given area and results in an overall higher data throughput on the satellite. In the VSAT configuration, the bandwidth is shared among a smaller group of users than Ku-band with typical data rates of around 1.0 to 20.0 Mbps. On average, the Ka-band satellites have the lowest cost per bit ratio, but they also enable significantly higher data rates compared to any other system, so overall costs may be higher. As with all satellite systems, a clear, unobstructed view of the satellite is required to operate.

Because Ka frequencies are almost twice the frequency used by Ku, the Ka-band is more susceptible to rain fades (i.e., loss of signal strength due to rain), but most systems are designed to operate in even the most severe of conditions with moderate degradation of service.

Appropriate terminals for the first responder community would include a 1.2 m (4 foot) satellite dish, positioner, satellite modem, and typically a small-scale network router (often built into the modem). There are also smaller class terminals on the market that use 75 centimeter (cm) (30 inch) satellite dishes, but they will have an inherently lower data rate and resilience to rain fades due to the smaller size. The terminals are designed to be mostly automated, but they do take a certain amount of training to operate and ensure proper positioning. Depending on the service agreement and support contract, the user may be required to phone the service provider when activating the system. This would require either access to a terrestrial phone network or satellite phone.

An interesting feature of commercial Ka-band satellite access is that the uplink and downlink frequencies are directly adjacent to military Ka-band satellites. It has been shown that properly-designed terminals can support both military and commercial Ka-band satellites. Depending on the design of the Ka-band terminal, it is reasonable to assume that in times of great urgency the first responder community may be given access to military Ka-band satellites.

### Messenger Services

While many of the previously discussed services support text messaging, there are services and devices dedicated to messaging that are worth discussing for the first responder community. There are two classes of messenger services: person messengers and fleet asset tracking (i.e., long haul trucks).

The SPOT messaging service, a personal messenger service and subsidiary of Globalstar, allows a user to send short messages either by typing them out on the device or providing longer pre-defined messages with a small hand-held device. These messages can be used to call for help or to communicate with a select contact group by e-mail, SMS, or even Twitter and Facebook. The devices can also be configured to report GPS positioning periodically to a Web service like Google Maps. The SPOT messaging service costs $0.10 per message if bought in bulk or as much as $0.50 for individual messages. The GPS tracking is $50 per year of service. The system is a one-way method of communication, however, and cannot receive messages. SPOT sells a separate device that can interface with an existing iPhone or Android in order to send messages from a smartphone.

GeoPro sells a two-way messaging device that uses the Iridium network. The service costs as little as $0.07 per message, charged on a monthly basis, and GPS tracking messages are included in this package.

Fleet asset tracking systems are used by both long haul trucking fleets and the U.S. Armed Forces (e.g., Blue Force Tracking). Blue Sky Network and Fleet Management Services both offer an Iridium-based system that provides GPS tracking and real-time text messaging between the central office and the asset being tracked. Costs depend on the fleet size and amount of messaging but are typically more than personal messengers because they offer a more complete service.

### 3.2.3 Network Considerations in SatCom

Satellite terminals either include network equipment (e.g., wired or wireless router) or provide an interface (e.g., serial, USB) to connect with external network gear. This provides the end users a wide variety of options in utilizing the network capacity by building the LAN of their design at the remote site.

It is crucial to have a network plan that matches the requirements of the users as well as the capabilities of the satellite (and other) services available. Table 7 lists relative purchase and data rate costs for each service.

**TABLE 7**

**Quick Reference Comparison of Satellite Communication Hardware**

| | Data Rate | Setup Time (minutes) | Size | Terminal Costs | Data Cost per Bit or Message |
|---|---|---|---|---|---|
| Ka-band VSAT | 2–20 Mbps | 30–60 | 2–3 transit cases | $100k–$300k | $$ |
| Ku-band VSAT | 0.5–4 Mbps | 30–60 | 2–3 transit cases | $100k–$300k | $$–$$$ |
| BGAN | 400 Kbps | 10 | Laptop or truck mounted | $5k–$30k[*1] | $$$$ |
| Messenger | 2.4 Kbps | <1 | Cell phone | <$1k | $[*2] |

[*1] Costs depend on which terminal is desired. Truck-mounted ones are significantly more expensive than man-portable units.

[*2] Costs are based on per message rate, similar to a cellular text message.

**Transmission Control Protocol over Satellite Links**

Traditional networking protocols struggle to make efficient use of satellite capacity. One of the fundamental protocols of Internet traffic is known as the TCP. A major portion of Internet traffic, including all HTTP traffic, uses TCP. While TCP has shown remarkable resilience in the face of the growth of the Internet, the performance of TCP suffers on links with long bandwidth-delay (BD) paths. Delay affects TCP disproportionately because TCP depends on acknowledgments from the receiver in order to adjust the transmission.

A TCP sender is dependent on timely network feedback to increase the rate at which it sends packets. With a delay as high as 0.5 seconds round-trip time for GEO satellites, TCP will take a considerable amount of time to increase the data rate to make full use of the available capacity.

Another issue with TCP is in dealing with a high BD product. The product of the bandwidth and delay determines how much unacknowledged data to resend in order to fully utilize the link. For a satellite link, the BD product can be high, and a TCP sender must be capable of handling a very large transfer window. For example, a 10 Mbps link with a 0.5 second round-trip time would have a BD product of 5 MB. A sender would need to have a window configured to at least this size in order to make full use of the available capacity.

Finally, TCP was designed for terrestrial networks where packet loss is almost always a symptom of congestion. When TCP detects a lost packet, it assumes there is congestion on the network and backs off the rate at which it sends packets. On a satellite channel, there may be other reasons—such as atmospheric conditions, interference, or weak signals—that cause a lost packet. Unfortunately, TCP will see this transmission error as a sign of congestion and reduce the throughput.

These are all well-known issues with TCP, and the Internet research community has been working on solutions for many years. Some solutions involve improvements to the TCP protocol itself. These protocol improvements can provide the most significant improvement in utilization, but require upgrades to each end user's computer or device.

For example, an extension to TCP called Selective Acknowledgments was developed by the research community; the extension enables a TCP receiver to notify the sender of specific segments that were lost so that the sender may retransmit them without having to back off on the data rate. Fortunately, this protocol has seen wide implementation since Windows 98 and Mac OS X 10.4, and most end users' systems are capable of this protocol. This protocol, however, does not alleviate all the problems described above.

The Internet Engineering Taskforce (IETF) Request for Comments 4614 (RFC 4614) provides a brief summary of the documents defining TCP and various TCP extensions that have accumulated in the IETF community. Specifically, Section 3 of this RFC lists recommended enhancements, many of which have been adopted by industry, and Section 6.2 lists enhancements for difficult networking environments, including satellite links.

**Performance Enhancing Proxy**

Since upgrading each end-user system is often infeasible, a popular solution to improving network performance in satellites networks is to use PEPs. A PEP is a hardware or software solution that is deployed at terminals in order to aggregate traffic and provide better service over the satellite link. The advantage is that all users behind a terminal can get the benefit of the improved performance without upgrades to each individual machine.

In addition to alleviating the TCP issues described above, PEPs are capable of improving the performance of certain applications such as Web traffic by techniques like caching and compression.

The primary characteristics of VSAT networks that PEPs can address include the high delay, the large BD product, and the issue of asymmetric capacity. In modern VSATs the outroute capacity is significantly larger than the inroute capacity. Since TCP requires acknowledgments from the receiver, the inroute acknowledgments place a significant burden on the inroute capacity.

VSAT vendors often integrate PEPs with the other features of their terminals. In addition, third-party PEPs are also available for use with VSATs.

PEPs commonly improve TCP performance by terminating the TCP connection at the PEP and then using a separate optimized protocol to transport the data over the satellite link. By splitting the TCP connection in this manner, a PEP can provide local acknowledgments and retransmissions in order to make rapid and efficient use of the available capacity.

VSAT PEPs often use some form of compression, which reduces the amount of bandwidth required. While some PEPs will compress data based on the application (e.g., Web/HTTP), compression is often performed at the link layer.

For BGAN service, Inmarsat offers a software TCP Accelerator product that splits the TCP connection as described above. This product runs on a PC, and in addition to splitting the TCP connection, it improves performance through other techniques such as TCP "fast start," TCP window spoofing, and optimized acknowledgement timeouts.

TCP "fast start" is a technique that overcomes the issue of TCP taking time to make full use of the available capacity. With "fast start," the user can transmit at full rate right away. The PEP at the receiver end performs window spoofing, which increases the number of packets in-flight at any given time, which increases the utilization of the link. Finally, the TCP accelerator can optimize the timeouts at the sender. TCP waits for acknowledgments for a certain duration, called the "timeout." In networks with large delays, the timeout can be optimized to compensate for the high round-trip time.

It is important to note that a PEP design may be at odds with a fundamental architectural principle of the Internet known as the end-to-end argument. This argument states that certain required functions, such as security and reliability, are best performed by the end systems themselves. For example, by spoofing acknowledgments to the sender, the PEP is acknowledging a packet that may not actually reach its intended recipient. This puts an additional burden on the applications to recover from a less reliable transport layer.

Also, because TCP PEPs rely on breaking the TCP connection, they are not compatible with certain security schemes that operate at lower layers such as the network layer Internet Protocol Security, since they render the TCP headers unintelligible through encryption. Hence, Internet Protocol Security (IPsec)-encrypted traffic (e.g., virtual private networks) may not be able to take advantage of the performance improvements made possible by PEPs. Certain PEP and VSAT providers have developed solutions, such as placing the PEP prior to encryption in the network. This may not be feasible in all network configurations, and must be analyzed further if IPsec is part of a user's network strategy.

## 3.3 WIRELESS NETWORKING TECHNOLOGY

As mentioned in the previous section, SatCom often terminate in a wireless router that is then the access point to the Internet. However, these routers have a relatively small range, and most cannot support responders even a few hundred feet away. Further, it is impractical and prohibitively expensive to equip each responder with a SatCom unit of their own. In a response where terrestrial infrastructure is not significantly compromised, the use of 4G LTE or similar technology allows responders to access cell phone towers miles from their location. There has been notable research on the construction of Hastily Formed Networks (HFNs), which take advantage of WMNs. This section discusses those options.

### 3.3.1 Landscape

Recent disasters, whether natural or man-made, have caused Congress to review its role in facilitating seamless first response and emergency personnel communication. The consequences of failure have grown. Congress recently passed the Middle Class Tax Relief and Job Creation Act of 2012 [4], which includes provisions for planning, building, and managing a new nationwide broadband network for public safety communications and assigned spectrum to accommodate the new network. The act plans to appropriate $7 billion from the auction of spectrum licenses for the new network and other public safety needs. The act has also mandated that the technical standards for the new network incorporate commercial standards for 4G LTE wireless technology that bases its operating standards on IP. However, clear policy on the spectrum for public safety and commercial use of this high-capacity and resilient packet-switched network remains a challenge. Although mission-critical voice communications will be carried on separate networks in the near term, the vision is that IP standards will replace standards for land mobile radio (LMR).

The act has given broad powers to the First Responder Network Authority (FirstNet) to build and maintain this visionary network while keeping it up to date with new technologies. In addition, several federal agencies have been designated to provide consultation and support, including the Federal Communications Commission (FCC), National Telecommunications and Information Administration, National Institute of Standards and Technology, and DHS Office of Emergency Communications [4].

### 3.3.2 Spectrum

There are several public safety bands that will be available, including: broadband (700 MHz), interoperable narrowband (700 MHz), and narrowband communications at the 800 MHz band. In addition to the three spectrums at the 700 and 800 MHz bands, there is 50 MHz available at the 4.9 GHz band for public safety [4].

**700 MHz Band**

Congress has designated 22 MHz in the 700 MHz band to support a broadband communications network for public safety. This spectrum is to be assigned to FirstNet by the FCC. Combined with 12 MHz of narrowband used primarily for voice, the total spectrum in the 700 MHz band is 34 MHz. While it is possible that all public safety spectrum at the 700 MHz band will be assigned to support broadband, there is no tested technology to deliver Voice over Internet Protocol (VoIP) that meets first responder needs, yet this is the future vision. There is much work for standardization in this band between public safety and commercial companies [4].

**800 MHz Band**

There is existing narrowband spectrum for public safety at this band [4].

**4.9 GHz Band**

In addition to these bands, 50 MHz of spectrum is available for public safety communications at the 4.9 GHz band. Current technology limits the use of this band to LANs that cover a small area [4].

**License Exempt Bands (2.4 and 5.2 GHz)**

There is 83.5 MHz of license-exempt spectrum in the 2.4 GHz industrial, scientific, and medical (ISM) band and 300 MHz in the 5.2 GHz Unlicensed National Information Infrastructure (U-NII) band [5].

### 3.3.3 Wireless Technologies

**IEEE 802.11 WiFi**

WiFi "hotspots" are seemingly ubiquitous today. Hotspots are wireless LANs that provide broadband service wirelessly to WiFi-equipped devices.

**Advantages**: WiFi is an IEEE standard for WLANs that is easy and cheap to deploy. Any device certified by the Wi-Fi Alliance (a nonprofit international association that certifies products that conform to IEEE standards of interoperability) is backwards compatible and can operate anywhere in the world. Also, WiFi can join a WMN to expand the reach of an ad hoc network. Although discussed later, WiFi can be one part of the solution to provide public safety communications for a disaster response.

**Disadvantages**: Range is a limitation of WiFi due to low transmit power requirements. In addition, interference can be a major issue, especially with neighboring devices operating on the same band and in the same channel. Also, WiFi makes use of the limited license-exempt bands, like some security cameras, Bluetooth devices, cordless phones, and baby monitors.

## TABLE 8

## IEEE 802.11 Standards [6]

| IEEE 802.11 Standard | Release Year | Frequency (GHz) | Bandwidth (MHz) | Maximum Data Rate Per Stream (Mbps) | Maximum Indoor Range (m) | Maximum Outdoor Range (m) | Modulation | Allowable MIMO* Streams |
|---|---|---|---|---|---|---|---|---|
| - | 1997 | 2.4 | 20 | 1, 2 | 20 | 100 | DSSS[*2], FHSS[*3] | 1 |
| a | 1999 | 5 | 20 | 6, 9, 12, 18, 24, 36, 48, 54 | 35 | 120 | OFDM[*4] | 1 |
| | | 3.7 | | | - | 5000 | | |
| b | 1999 | 2.4 | 20 | 1, 2, 5.5, 11 | 35 | 140 | DSSS | 1 |
| g | 2003 | 2.4 | 20 | 6, 9, 12, 18, 24, 36, 48, 54 | 38 | 140 | OFDM, DSSS | 1 |
| n | 2009 | 2.4, 5 | 20 | 7.2, 14.4, 21.7, 28.9, 43.3, 57.8, 65, 72.2 | 70 | 250 | OFDM | 4 |
| | | | 40 | 15, 30, 45, 60, 90, 120, 135, 150 | | | | |
| ac draft | ~2014 | 5 | 20 | <87.6 | | | | 8 |
| | | | 40 | <200 | | | | |
| | | | 80 | <433.3 | | | | |
| | | | 160 | <866.7 | | | | |
| ad draft | ~2012 | 60 | | <7000 | | | | |

[*1] MIMO – Multiple-Input and Multiple-Output
[*2] DSSS – Direct-Sequence Spread Spectrum
[*3] FHSS – Frequency-Hopping Spread Spectrum
[*4] OFDM – Orthogonal Frequency-Division Multiplexing

Additionally, both the IEEE 802.11ac and ad standards are in draft. IEEE 802.11ad plans to add the 60 GHz band to the traditionally used 2.3 and 5 GHz frequency bands. IEEE 802.11ad has the potential for multi-gigabytes per second (Gbps) connection speeds as opposed to the IEEE 802.11ac standard that promises ~1 Gbps speeds.

**IEEE 802.16 WiMax**

To address the limited range and interference acceptance requirements of WiFi, WiMax was born. Both technologies boast broadband IP access with the ability to facilitate a WMN.

**Advantages**: In general, WiMax includes an embedded quality of service and centralized network control, contrary to WiFi. In addition, WiMax has evolved into fixed and mobile applications that can service hundreds of users. WiMax is a standard looking for spectrum. It can be operated in many bands, licensed or license-exempt. For instance, extending WiMax to the 4.9 GHz and 700 MHz bands is being considered. WiMax was also deployed to assist with communications after Hurricane Katrina and the 2004 tsunami in Indonesia. Finally, WiMax is more secure than LTE as it uses strong authentication protocols and can be used as a wireless backhaul [5].

**Disadvantages:** Weather and appliances can affect the signal quality depending on what bands the signal is using. Also, data rates are inversely proportional to the service range. Finally, non-line-of-sight users need to be close to the base station, while users at a distance need to be in the line of sight (LOS).

**TABLE 9**

**IEEE 802.16 Standards [5]**

| IEEE 802.16 Standard | Release Year | Frequency (GHz) | Bandwidth (MHz) | Maximum Data Rate (Mbps) | Maximum Range (km) | Modulation | Service |
|---|---|---|---|---|---|---|---|
| - | 2001 | 10–66 | | 134 | LOS < 5 | OFDM, OFDMA*1 | Fixed |
| d | 2004 | <11 | 1.75, 3.5, 5, 7, 10, 20 | 70 | LOS < 30, Non-LOS < 5 | OFDM, OFDMA | Fixed / Nomadic |
| e | 2005 | <6 | 1.25, 2.5, 5, 7, 10, 14, 20 | 35 | Non-LOS < 10 | SOFDMA*2 | Fixed / Mobile |
| m | 2011 | <6 | 20,40 | <1000 fixed, <100 mobile | Non-LOS < 30 | SOFDMA | Fixed / Mobile |

*1 OFDMA - Orthogonal Frequency-Division Multiple Access

*2 SOFDMA - Scalable Orthogonal Frequency-Division Multiple Access

Additionally, IEEE 802.16m specifies true 4G functionality with up to 1 Gbps fixed and 100 Mbps mobile data rates.

**Long Term Evolution**

LTE is a standard developed by the 3rd Generation Partnership Project (3GPP).

**Advantages:** Most of the world has adopted the LTE standards for reliable cellular communication as opposed to WiMax. Also, the U.S. Government has mandated that LTE be used in the construction of a new first responder network. Like WiMax, LTE is a flat IP network architecture.

**Disadvantages:** LTE is not as secure as WiMax because it uses EAP_AKA or UMTS_AKA authentication protocols as opposed to WiMax using EAP_TTLS or EAP_TLS [7]. LTE is also more costly to deploy and maintain than WiMax.

**TABLE 10**

**The Evolution of LTE Advanced from 3G Technologies [8]**

| Technology | Maximum DL (bits per second [bps]) | Maximum UL (bps) | Latency (approximate round-trip time) | 3GPP Releases | Rollout (approximate year) | Modulation Technology |
|---|---|---|---|---|---|---|
| WCDMA* | 384 k | 128 k | 150 ms | 99/4 | 2003/2004 | CDMA*2 |
| HSPA*3 HSDPA*4/ HSUPA*5 | 14 M | 5.7 M | 100 ms | 5/6 | HSDPA – 2005/2006, HSUPA – 2007/2008 | CDMA |
| HSPA+*6 | 28 M | 11 M | 50 ms | 7 | 2008/2009 | CDMA |
| LTE | 100 M | 50 M | ~10 ms | 8 | 2009/2010 | OFDMA/ SC-FDMA*7 |
| LTE Advanced | 1 G | 500 M | <5 ms | 10 | Current | OFDMA/ SC-FDMA |

*1 WCDMA - Wideband Code Division Multiple Access
*2 CDMA - Code Division Multiple Access
*3 HSPA - High Speed Packet Access
*4 HSDPA - High Speed Downlink Packet Access
*5 HSUPA - High Speed Uplink Packet Access
*6 HSPA+ - Evolved High Speed Packet Access
*7 SC-FDMA - Single-Carrier Frequency-Division Multiple Access (FDMA)

Additionally, like IEEE 802.16m, LTE Advanced specifies true 4G functionality with up to 1 Gbps fixed and 100 Mbps mobile data rates. Also, the LTE Advanced specification includes the concept of heterogeneous network deployments where the coverage area of a macrocell is enhanced by adding smaller base stations with less coverage. This topic is covered in more detail in subsequent sections.

### 3.3.4 Applications to Disadvantaged Communications

***Wireless Mesh Networks***

WMNs are communication network nodes that can be set up in an overlapping pattern to relay and route information to nearby nodes. They are easy and cost effective to set up and usually make use of license-exempt spectrum. A WMN's architecture can be composed of infrastructure-mesh and client-mesh networks. The client-mesh network node is synonymous with an ad hoc network node where each client-mesh network node can come or go and relays or routes traffic to nearby network nodes. Infrastructure-mesh network nodes route information from client-mesh network nodes outside the ad hoc network [9].

While a WMN solves some problems with its flexible and scalable principles, it also introduces some questions. Some nodes of the WMN could be privately or publicly maintained. When a disaster occurs, who gets priority? How is the WMN maintained? How is the WMN deployed to obtain the most complete coverage for first response [9]?

### *WiMax*

The WiMax specification includes a mesh mode of operation and could serve as an effective wireless backhaul for disaster response when no other communication methods are available. Consider a network of WiMax stations, each equipped with two transceivers—one to establish the backhaul mesh and one to establish communications with its peers. Both transceivers should be on different bands so as not to interfere. In a WMN, it might be necessary to prevent any stations connected by two hops from transmitting on the same frequency. It should also be noted that distances between nodes will affect the backhaul data link capabilities and care must be given when considering the data requirements that must be met in a two-tier command and control architecture as described above. Will peers need voice, video, and data? Will command have similar data requirements? In most command and control hierarchies, the majority of communication happens in the lowest level among peers [10].

WiFi has the same types of constraints but could be used in conjunction to establish a hybrid WMN to extend coverage to harder-to-reach areas and end users. In this three-tier network architecture, a WiMax backhaul is used in the point-to-point (PTP) mode between the Internet and a point-to-multipoint (PMP) WiMax base station. The PMP base station is used to set up a WiFi access point and a WiFi WMN between MSSs. The next two graphics illustrate the latter and the grand vision that could be useful to an ad hoc first response network when communications are compromised [11].

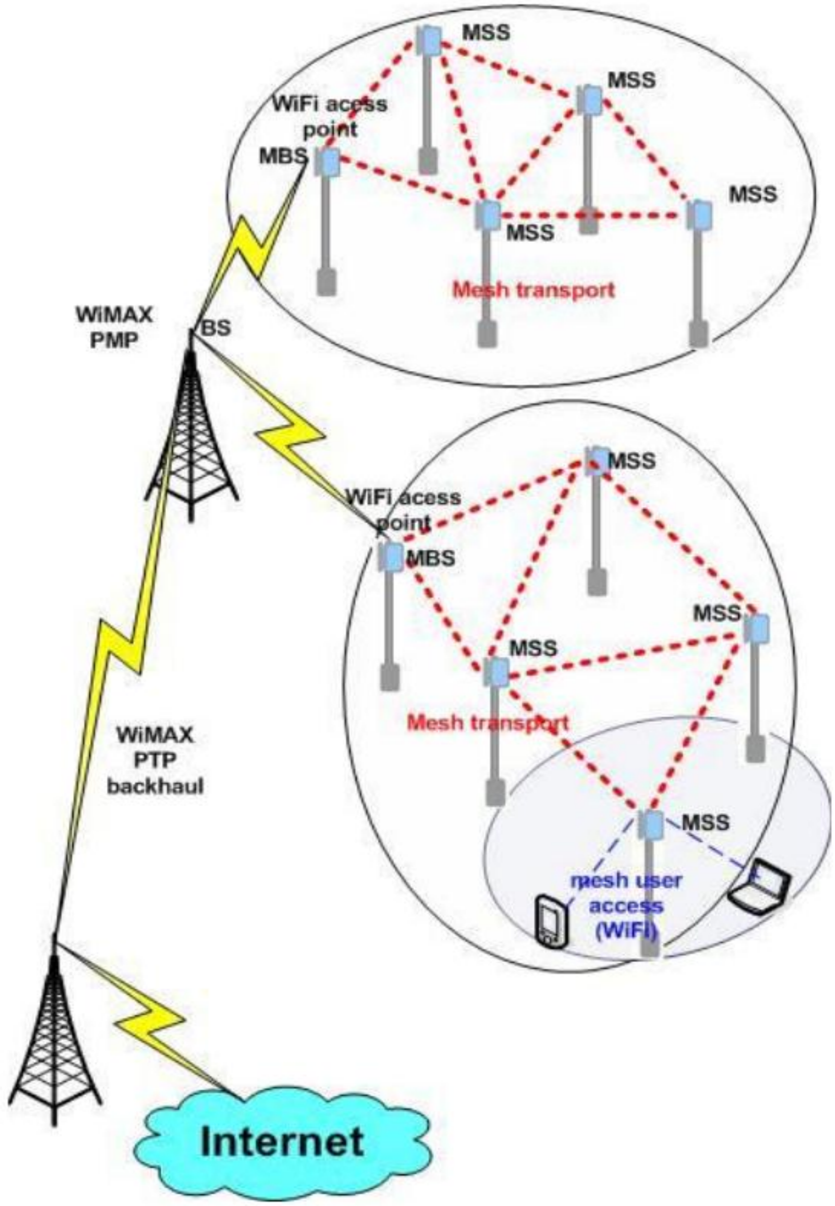



*Figure 5. WiMax PTP backhaul and PMP base station [11]*

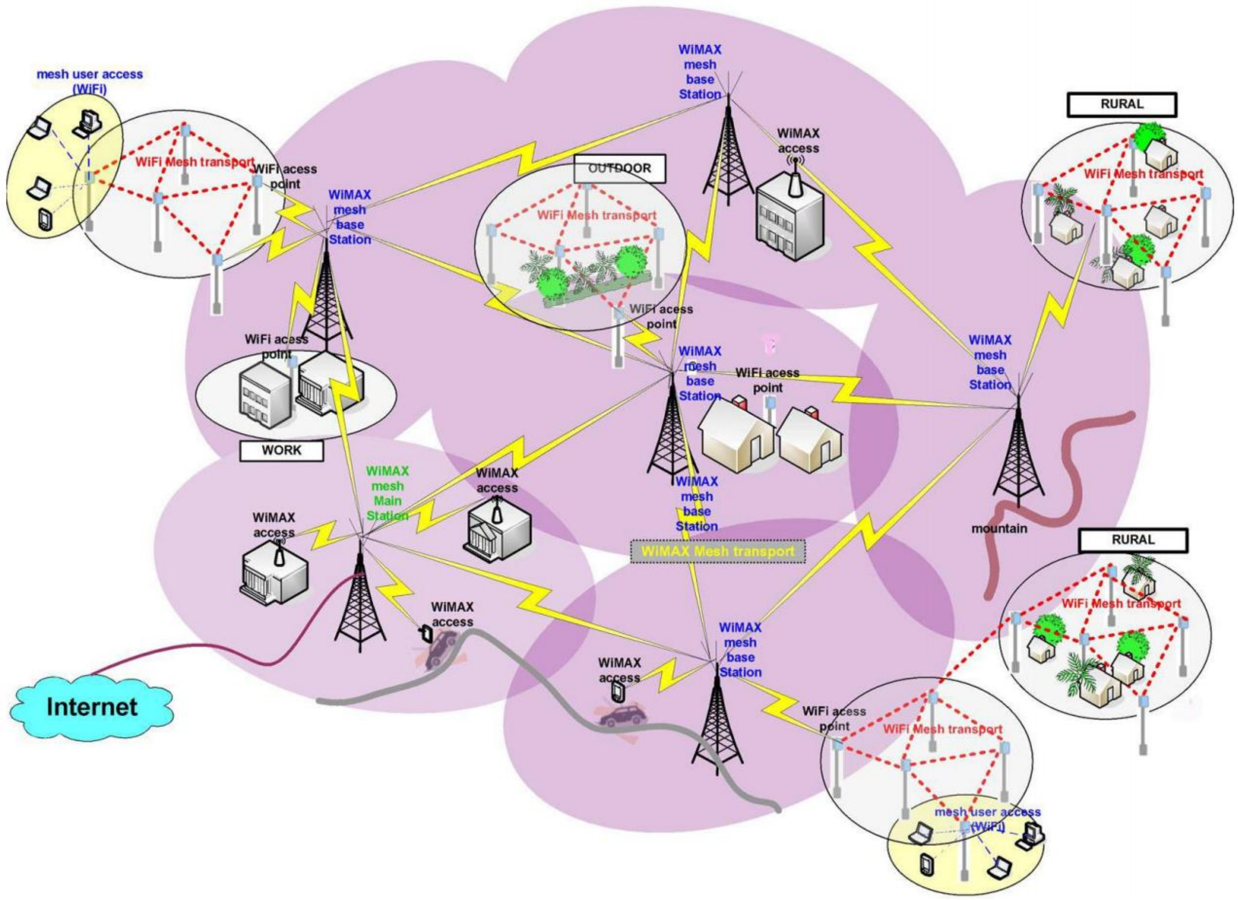



*Figure 6. A possible first response network architecture [11]*

### *LTE*

The LTE Advanced specification includes the concept of heterogeneous network deployments where the coverage area of a macrocell is enhanced by adding smaller base stations with less coverage. These smaller base stations are categorized by coverage and capacity as micro, pico, and femtocells. Some typical small cell locations could be on lampposts or on streetside buildings to extend coverage in an urban environment. In order to ensure good quality of service, LOS from the macro to the small cell is necessary, but not very practical. There are many WiMax challenges within the LTE design, and no real solution yet exists. However, a route and relay solution between small cells may resolve some of these challenges and it is currently under investigation as an alternative. Deployment of a wireless backhaul with small cells suffers from both system and weather interference similar to WiMax as license-exempt bands are most attractive. Finally, mesh topologies offer the most flexibility and resiliency if the quality of service is acceptable [12].

### 3.3.5 Wireless Conclusions

In conclusion, both WiMax and LTE have strong characteristics for enabling communications. FirstNet and the U.S. government have mandated the use of LTE for the build-out of a new first responder network alongside existing commercial networks and to keep it up-to-date with new technologies. This indicates a partnership with commercial service providers. Is this new network susceptible to the same communications failures of the commercial networks when a disaster strikes?

LTE has an advantage over WiMax because it operates in the licensed spectrum of the 700 MHz band, which greatly reduces the possibility of interference and has better wave propagation properties. However, it is predicted that the 700 MHz band will not support fixed broadband streaming applications even if public safety gives an additional 20 MHz of adjacent spectrum. It is argued that public safety is aware that the 700 MHz band is not about fixed broadband; rather, it is about incident broadband [13].

WiMax is a standard looking for spectrum (it has had limited deployment in the United States) and as a result can operate in many different bands, including license-exempt bands and potentially bands set aside for public safety communications. Operating in the GHz range could offer fixed broadband with low latency where some believe LTE will fall short in the 700 MHz band. However, the GHz range is more susceptible to weather and obstacle interference. Further, WiMax and WiFi would interfere with each other if deployed in the 2.4 or 5 GHz license-exempt bands.

WiMax has an advantage over LTE as it can operate in mesh mode. LTE Advanced is just now including in Release 10 a specification for heterogeneous network deployments. Although WMNs are not a new concept, they are now being researched as a resilient network architecture to work in combination with studies using wireless cells as backhauls or in mesh mode to reduce the costly installation of wire line backhauls. The results could be applied to restoring communications in a disaster.

# 4. SOFTWARE

In order to evaluate SatCom viability for disaster response scenarios, it is important to consider how software systems can be expected to operate using SatCom and discuss any design considerations to promote improved software performance under SatCom network characteristics. NICS, described in Section 4.1, was selected for this purpose. Developed in 2008, NICS provides first responders with a national-scale situational awareness system that emphasizes low-cost, open standards and low-bandwidth requirements. NICS began after a series of catastrophic fires in the 2000s when MIT LL conducted a series of case studies to identify sources of inefficiencies and lack of timely information in the field. NICS relies on a data connection between participants for the majority of the system's utility; a data connection is mandatory, but high-link bandwidth is not necessarily required. NICS has been designed to work in low-bandwidth field environments and is therefore an appropriate selection for this study.

## 4.1 THE NEXT-GENERATION INCIDENT COMMAND SYSTEM

NICS is an open, non-proprietary, distributed, scalable, Web-based situational awareness system for first responders. NICS was developed by MIT LL, in partnership with the California Department of Forestry and Fire Protection and under the sponsorship of DHS S&T. NICS was designed with field first responders in mind (i.e., disadvantaged communications, unanticipated equipment, and a "tired-dirty-hungry" user). NICS supports a thin client, which enables anyone with an Internet connection (via a cell-connection, WiFi, a satellite connection, etc.), a Web-browser, and log-in credentials to connect to the system; no specialized hardware or software is required. It also uses a lightweight client with small message sizes and store-and-forward capabilities.

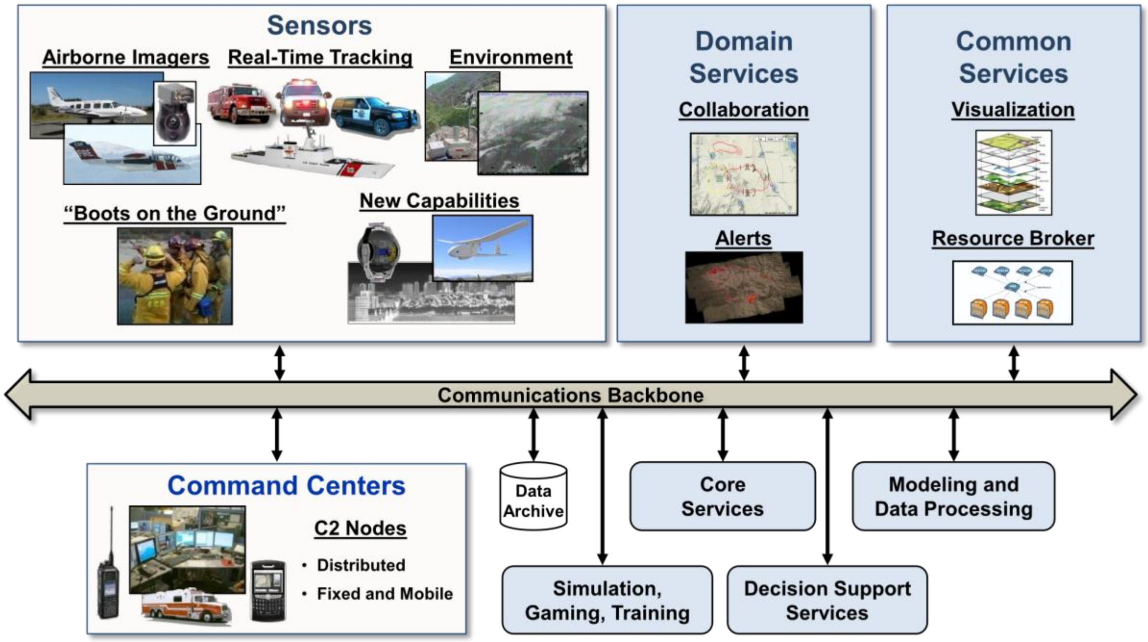



*Figure 7. NICS system*

## 4.2 APPROACH

NICS was chosen as a pathfinder software application to evaluate SatCom viability for disaster response scenarios because it is designed for first responders in the field, for use at formal incident command locations, and for higher command. NICS relies on a data connection between participants for the majority of the system's utility in the sense that a data connection is mandatory, but high-link bandwidth is not required.

Three field tests are outlined below, each with different SatCom hardware and software. In each test, the SatCom link speed and reliability was tested and qualitative NICS usage observations are provided. These tests represent an initial testing capability of NICS over a SatCom link. No modifications of the NICS software beyond what is already available in the production environment were used for these field tests. In the future, NICS could be modified to provide varying levels of functionality based on the communications link bandwidth and be further developed to maximize performance over intermittent link outages if SatCom is chosen as a priority for development.

# 5. FIELD EVALUATIONS

## 5.1 OVERVIEW OF SATCOM FIELD EVALUATIONS

Three field evaluations of NICS performance over SatCom systems were conducted in March, April, and December 2012, utilizing a number of VSAT Ku-band and BGAN terminals in different configurations. Following the first two evaluations, it was clear that passing large GIS map data files was problematic given the bandwidth-delay constraints of SatCom systems. The third evaluation was designed to examine several mitigating strategies, including testing new PEP software (see Section 3.2.3 for details) and configuring NICS so that only essential updates (i.e., not static map data) are transferred over the SatCom link. This latter configuration appears very promising for more effective connectivity via SatCom in disaster scenarios.

## 5.2 MASSACHUSETTS ARMY AND AIR NATIONAL GUARD COMMUNICATIONS EXERCISE, MARCH 2012

The first field evaluation was conducted during the Massachusetts Army and Air National Guard (NG) communication exercise (COMMEX) on March 4, 2012.

**Systems:**

The NG fielded two different SatCom systems at the COMMEX. The Army NG fielded an Armed-Forces-only VSAT terminal and the Air NG fielded the JISCC terminal.

The Army VSAT terminal is a flyaway Ku-band, 1.2 m auto-aligning SatCom terminal distributed by Globecomm. It uses an L-3-developed modem that incorporates iDirect modem technology, which is a server room-grade modem (i.e., not hardened for extreme conditions). (Note: iDirect is a SatCom modem manufacturer.) The Army VSAT terminal is completely self-sustained and supports both VoIP and Internet access. The VSAT is intended to require approximately 15 minutes to configure and connect to the network. It does not require an additional method of communication to establish connectivity with the network.

The terminal relies on a fixed ground site gateway maintained by Globecomm. The Globecomm gateway hosts the Army NG's modem and routes traffic according to its intended destination. The Internet traffic over the link is heavily filtered to meet the Army security requirements and is not intended for use by third parties (i.e., local first responders). In other words, it is an Army-NG-only system.

It appears that the modem in the VSAT terminal messaged the TCP/IP traffic to support the high-latency satellite channel.

The JISCC system is a nationally-deployed disaster relief terminal fielded to the states. Massachusetts currently has three JISCC terminals, which is exceptionally rare; most states have only one terminal. The terminals are fielded in self-contained, tow-behind trailers, with all the necessary equipment to support extended operation, including backup power systems (i.e., generators). The JISCC communication capabilities include, but are not limited to, Ku SatCom, VHF, UHF, high frequency (HF), and WiFi.

The Air NG JISCC SatCom system is very similar to the Army NG's VSAT terminal, but it is specifically intended for disaster relief. The terminal hardware is also very similar in that it is a flyaway Ku-band, 1.2 m, auto-aligning SatCom terminal distributed by Globecomm. The primary hardware difference is that the modem is integrated within the antenna pedestal and specifically hardened for severe weather conditions. The SatCom terminal is the primary method for Internet access. This connectivity is enabled by the remote Globecomm Gateway, just like the Army NG's VSAT terminal, but is not constrained by the same security rules. On site, the JISCC delivers Internet access to different users via a WiFi router. The WiFi router has multiple services to support different levels of service and security. They specifically support an unencrypted service to local first responders and aid agencies. This was the link used by the NICS team to test the execution of their application.

**Result:**

The COMMEX test event appeared to be a very successful event for the NICS application. It is important to note that the satellite link performance experienced by the NICS application was at its best due to the exceptionally good weather and the fact that SatCom link was dedicated to NICS users. In a real disaster response, it is the opinion of the authors that the link performance would be dramatically lower due to resource sharing and possible weather outages.

## 5.3 NAVAL POSTGRADUATE SCHOOL COMMEX, APRIL 2012

The Naval Postgraduate School (NPS) conducted a COMMEX from April 3 to 5, 2012. The COMMEX commenced in Big Sur, California, at the Andrew Molera State Park. The intention of the testing was to quantify the quality of the NICS experience over SatCom.

**Systems:**

The California NG, Inmarsat Government Systems, and NPS provided SatCom communications. The NPS COMMEX fielded two different types of SatCom: VSAT and BGAN terminals.

The NG provided three VSAT terminals and Inmarsat provided a single VSAT terminal. All the terminals were 1.2 m, Ku-band dishes, offering at least 1 Mbps uplink and downlink data services. NPS provided a multitude of different BGAN terminals, but for the most part, they all function in a similar fashion with an upper data rate of approximately 400 Kbps.

**Result:**

The NICS application worked well on the lightly-loaded VSAT terminal. The VSAT terminals accelerated the NICS TCP/IP transactions and reduced the effects of the high-latency link. There were a few minor issues with the prepared test scripts' timing due to the high-latency link, but these were easily corrected in the field.

The NICS application did not perform well on the BGAN terminals. Depending on the computer settings (normal versus increased TCP window size), the map transfer portion of the application could take anywhere from 2.5 to 5 minutes. It took a bit of reworking to enable the automated test scripts to successfully execute. The assumed reason for the extreme latency was the use of TCP/IP over a high-latency link. Inmarsat offers a software PEP for the BGAN terminal and highly recommends it for any TCP/IP traffic. Unfortunately, the supported operating systems are rather limited and antiquated. The fielded laptops were not able to support the PEP software.

The link bandwidth test results verified that the TCP/IP protocols were severely limiting the transfer of the maps' data in a reasonable period of time. For the two UDP tests where UDP traffic was streamed at 100 and 200 Kbps, the BGAN link was more than capable of supporting the traffic. In the TCP test case, the BGAN link was not capable of sustaining anywhere near the UDP rates and was often less than 64 Kbps.

Transferring maps for NICS was an impediment to using the system, and NICS would benefit from data prioritization, local caching (e.g., maps), degrading map quality (and therefore requiring less data to be transmitted), developing a UDP version of the application, etc.

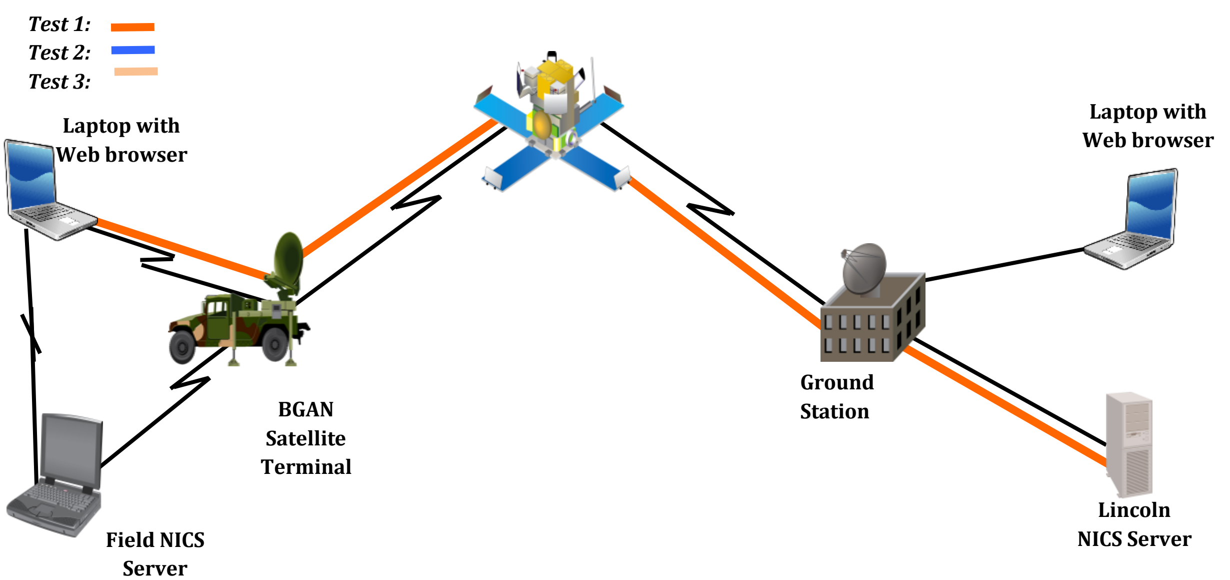
## 5.4 MITIGATION STRATEGY EVALUATION, DECEMBER 2012

In December 2012, NICS was tested with an iNetVu Ku-band, 1.2 m, auto-aligning SatCom terminal provided by the commercial vendor Skycasters. It used an iDirect modem designed for broadband speeds over SatCom links. The system was configured to provide IP through a standard off-the-shelf WiFi router, making connections to the system simple for most devices.

Setup of the system was straightforward. Employees from MIT LL experienced with SatCom systems completed system setup and configuration within an hour. Once the system was initially configured, knowledge for establishing a satellite connection and general operation was easily transferred to inexperienced personnel who were able to operate the system. The system was not weather-hardened, which made work difficult during adverse weather conditions. The system experienced downtime due to a water leak that caused the modem to malfunction. The system was successfully brought back online after being powered off and allowed to dry for a day.

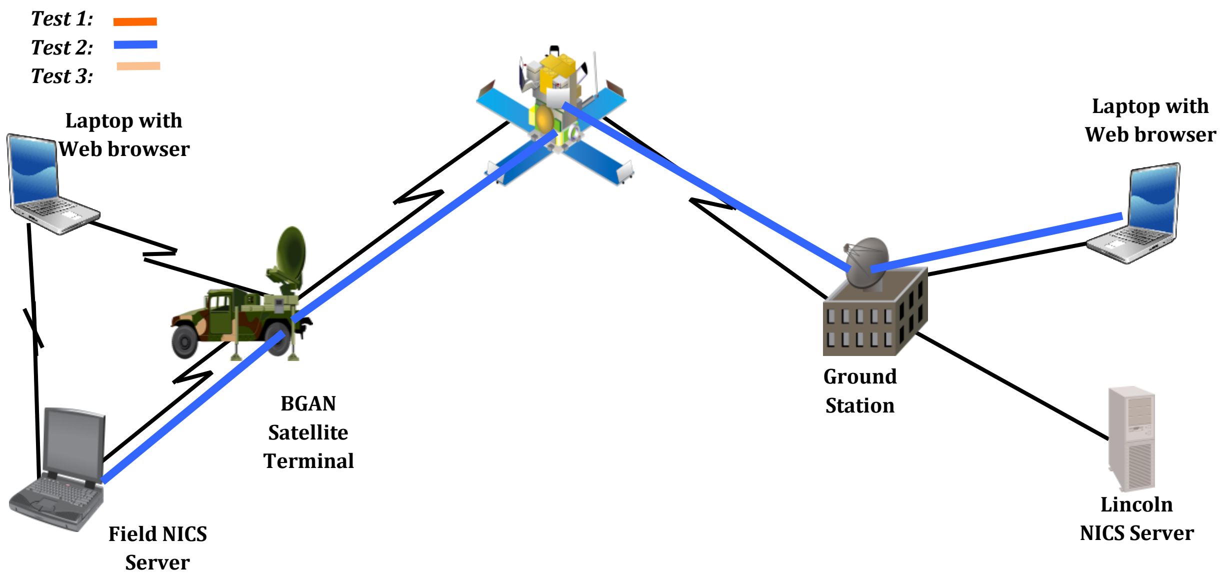
During the testing, a special NICS configuration was created to investigate potential NICS arrangements over a SatCom link. A NICS server was deployed onto a laptop along with a laptop map server. In this manner, a completely-contained NICS configuration was created that did not need an Internet connection for functionality. Users could connect to the local area connection to access and utilize NICS just as with the current production NICS system. The local map server provided base maps that were found in previous tests to use the most bandwidth. The satellite link in this scenario was used to allow collaborators to connect to the remote NICS server from any Internet connection. This method is robust to low bandwidth connectivity and disconnects because all data sent to each user is queued if there is a disconnection and resent upon reconnection to the system. Downsides to this method are that the SatCom link is not being used efficiently, as all user-connected data must be transmitted to provide updates. As a result, redundant data is being sent over the link.

Figures 8 through 10 show the NICS configurations and data transmission paths for the various SatCom testing scenarios evaluated.




**Test 1: Pre-loaded base maps: Evaluate NICS field performance with reduced bandwidth requirements/utilization enabled by map caching**

*Figure 8. Configuration of NICS SatCom evaluation for Test 1 of the December 2012 testing. This test examined NICS performance when maps were cached on the field-deployed laptop, reducing the bandwidth demands via the SatCom link.*




**Test 2: <u>Field-deployed NICS server</u>: Demonstrate isolated local field capability enabled over WiFi and off-site collaboration via SatCom**

*Figure 9. Configuration of NICS SatCom evaluation for Test 2 of the December 2012 testing. This test examined NICS performance when a NICS field server (on a laptop) was deployed so that maps did not have to be "pulled" from the MIT LL NICS server, reducing the bandwidth demands via the SatCom link.*

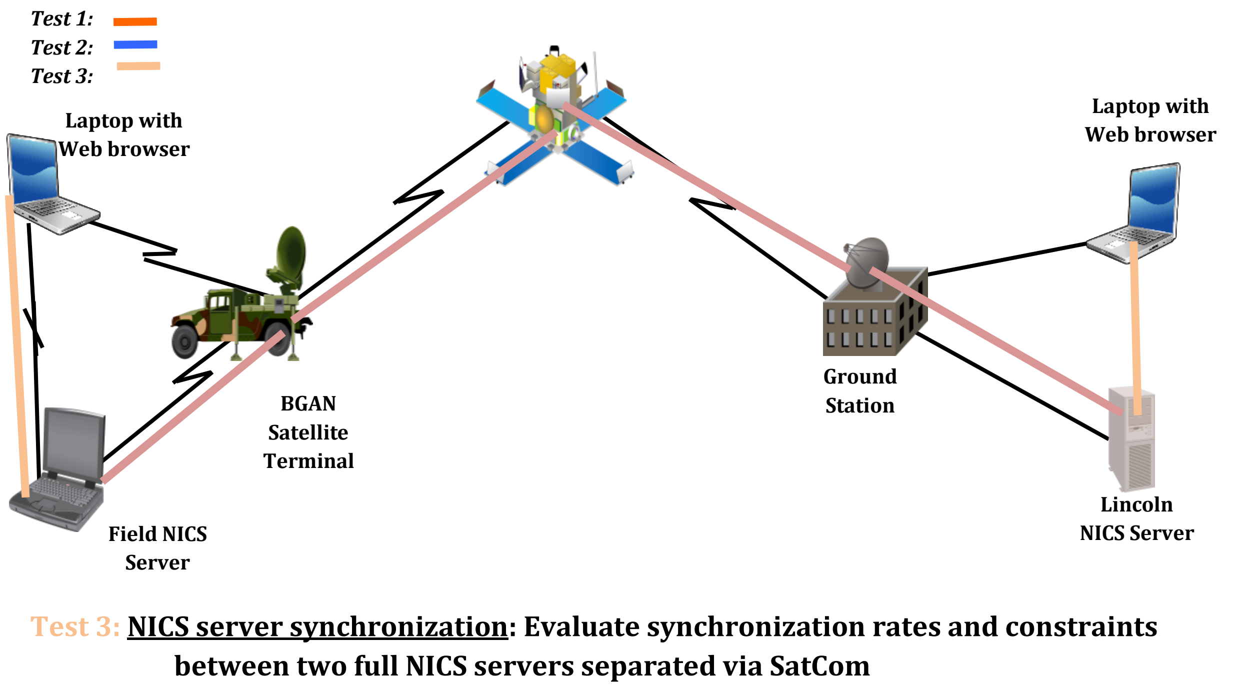



*Figure 10. Configuration of NICS SatCom evaluation for Test 3 of the December 2012 testing. This test examined NICS performance when a NICS field server (on a laptop) was deployed so that maps did not have to be "pulled" from the MIT LL NICS server, reducing the bandwidth demands via the SatCom link. Synchronization between additional field NICS users (via the field server) over the SatCom link with NICS collaborators accessing the MIT LL server was evaluated.*

**Result:**

Bandwidth tests of the connection showed good performance. TCP tests resulted in an average download speed of ~3.0 Mbps and an average upload speed of ~1.1 Mbps in good weather conditions. UDP tests showed similar results for the upload, error rates of approximately 4 percent for a 1 Mbps rate and below, with the error jumping up significantly to 50 percent at a 2 Mbps transfer rate. Download UDP transfers had errors of 1 percent or less for rates of 5.5 Mbps. These data rates provided acceptable performance for users connecting to NICS over the SatCom link. Two users could simultaneously log in and collaborate without any significant delays. However, two out of the eight days of operation resulted in poor connectivity due to inclement weather (snow and icy rain). During these days, the signal frequently disconnected, which resulted in poor network performance. It is expected that software systems that rely on network connectivity would not function under these conditions; this thesis was confirmed by unsuccessfully attempting to perform NICS bandwidth tests.

For the three configuration Tests (1–3) shown in Figures 8 through 10, remote users successfully connected to the remote NICS over the SatCom link and collaborated with acceptable performance. The standard NICS tests were run both from the LAN and from over the SatCom link. These tests are meant to put stress on the system by having multiple simulated users simultaneously log in and interact in the environment. These tests do not represent the actual number of users that may use the system at once; instead, they can represent a baseline to benchmark different configurations. On the LAN, three test users were able to run simultaneously, while over the SatCom link only one user was able to complete the test. These results agree with expectations as the LAN has much greater bandwidth and lower latency than the satellite link.

## 5.5 NEXT STEPS

The three SatCom tests have resulted in great experience gains from operating NICS in a disadvantaged communications environment. To be effective in this area, NICS must be robust to high latency, low bandwidth, and disconnected network environments, and provide utility even with no Internet connection. Results from the first two tests led to the deployment of a stand-alone, remote NICS system that could allow any user to connect when paired with a SatCom link. The next step is to increase system efficiency when using a SatCom link. One approach is to have two NICS nodes operating on either end of the SatCom link. Users on either side would connect to their respective NICS node. The two NICS implementations will handle syncing activity on either side in an efficient and robust manner.

# 6. COMPLEMENTARY APPROACHES

## 6.1 FCC DEPLOYABLE AERIAL COMMUNICATIONS ARCHITECTURE

The FCC is investigating potential opportunities to support a Deployable Aerial Communications Architecture during incident and disaster response to restore critical communications [14]. According to the FCC, a catastrophic event could involve the power grid, which may be inoperable for five to seven days, leading to a depletion of back-up power sources. This will likely result in an almost complete failure of conventional communication platforms, including landline, cellular, LMR, broadcast, cable transmissions, WiFi, and Internet services. In certain circumstances, access to roads and bridges may be impassable, preventing the transport of fuel and generators. The FCC envisions a deployable aerial capability within the first 12 to 18 hours after a catastrophic event tasked with restoring critical communications. This initial deployment would also support broadband data services for a period of 72 to 96 hours [14].

Under these catastrophic conditions, the FCC identified UAS, aerostats, and deployable "suitcase" systems as candidate deployable communication technologies to address this capability gap. All three technologies can support SatCom operations. Many SatCom systems already operate as a deployable suitcase system. An aerostat—an airborne system that remains aloft using aerostatic buoyancy (e.g., a moored balloon) —is ideal for long endurance operations. Recent efforts have explored the use of aerostats that can be deployed from a standard vehicle or mobile platform [15, 16, 17, 18]. However, aerostats rely on power provided through a tether and still face mobility concerns. It is difficult to deploy a system without vehicle access. Additionally, it is difficult to ruggedize an aerostat for operations in extreme environments, such as a wildland fire.

A UAS can act as a mobile and rapidly-deployable communication platform; however, its communication capabilities are directly dependent on the aircraft's size, weight, and power. A large "Global Hawk" can act as a long-endurance SatCom repeater over a city, whereas a small hand-launched aircraft may only provide a few hours of communications over a few miles [19].

Any aerial platform can enhance SatCom operations. Foremost, aerial platforms can elevate radios or antennas above ground level; this reduces clutter or multi-path problems and improves LOS connectivity. Second, the deployable nature of aerial platforms enables users to establish connectivity in many field environments, complementing the near-ubiquitous SatCom connectivity.

## 6.2 UNMANNED AIRCRAFT SYSTEMS

Small unmanned aircraft systems (SUAS) have high potential as a safe and non-intrusive tool to supplement many current DHS and first responder operational components [20]. SUAS have a wide range of capabilities, whether fixed wing or rotorcraft, gimbaled or body-fixed sensors, and discrete or mixed payloads. SUAS vary in cost, weight, endurance, complexity, and overall reliability. SUAS for first responders are generally less than 25 pounds gross take-off weight, with some considerations for heavier aircraft, and will operate up to 400 feet above ground level. Current Federal Aviation Administration (FAA) regulations do not permit "file-and-fly" UAS operations. All UAS activities must operate under a limiting certificate of authorization (COA). Figure 11 illustrates law enforcement organizations with active COAs; however, an active COA does not indicate operational use.

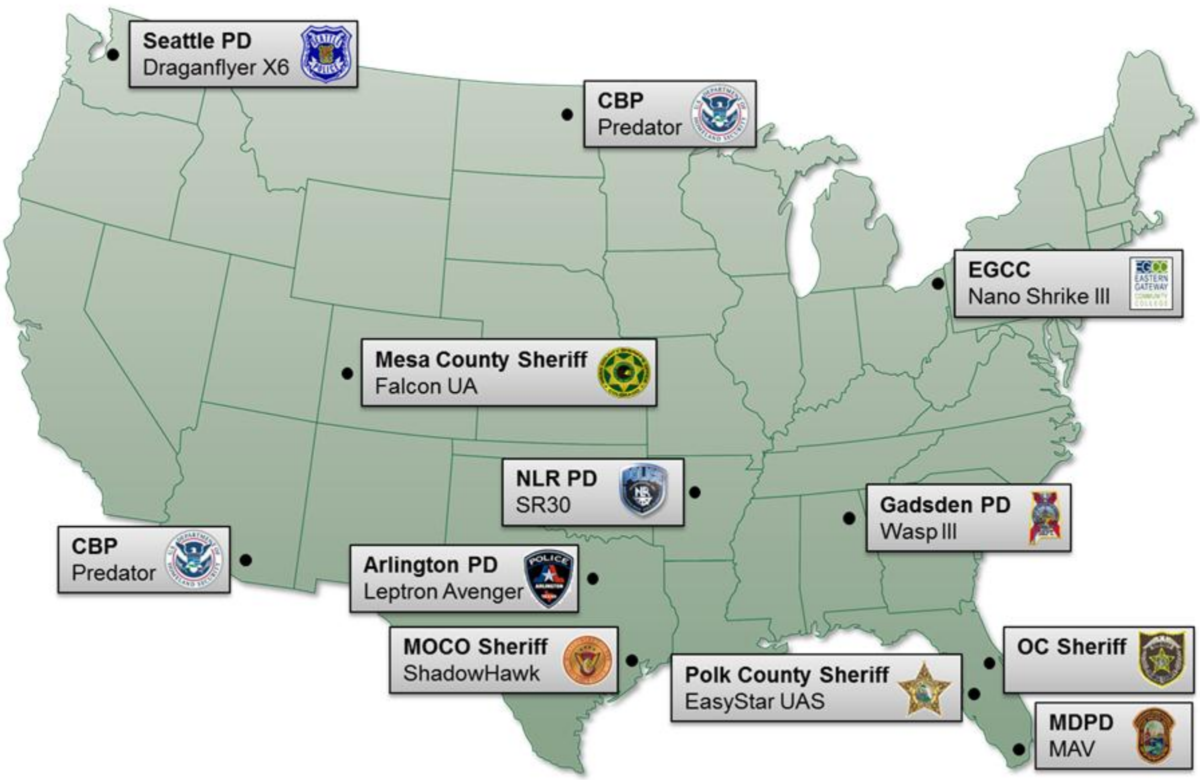



*Figure 11. Active law enforcement COAs as of December 11, 2012*

Tables 11 and 12 detail the SUAS used by these organizations, which are generally split between hand-launched, fixed-wing platforms and vertical take-off and landing (VTOL) platforms. The fixed-wing aircraft are generally lighter, while the VTOL platforms have greater payload capacity. These low-altitude, short-endurance UAS are relatively simple to operate but have short-duration operational capabilities of 45 minutes to 2 hours [21]. In addition to endurance limitations, smaller aircraft are more susceptible to environmental conditions such as wind, fire, and precipitation. These limited capabilities are in contrast to the longer-endurance, larger Predator and Global Hawk unmanned aircraft.

**TABLE 11**

**Hand-launched Fixed Wing UAS**

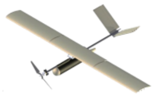
| Platform | User | Weight | Capacity | Image |
|---|---|---|---|---|
| **Williams Aerospace Nano Shrike III** | Eastern Gateway Community College | 0.80 lbs | 0.035 lbs |  |
| **AeroVironment Wasp III** | Gadsden Police Department | 0.95 lbs | Cameras |  |
| **EasyStar** | Polk County Police Department | 2.1 lbs | Unknown |  |
| **Falcon UAV** | Mesa County Sheriff | 7.0 lbs | 2.0 lbs |  |

**TABLE 12**

**Vertical Take-off and Landing UAS**

| Platform | User | Weight | Capacity | Image |
|---|---|---|---|---|
| **Leptron Avenger** | Arlington Police Department | Unknown | 10 lbs |  |
| **Draganflyer X6** | Seattle Police Department | 2.2 lbs | 1.1 lbs |  |
| **Honeywell RQ-16A MAV** | Miami-Dade Police Department | 16 lbs | Cameras |  |
| **Vanguard ShadowHawk** | Montgomery County Sheriff's Department | 49 lbs | 22 lbs |  |
| **Rotomotion SR30** | North Little Rock Police Department | Unknown | 15 lbs |  |

The unmanned aircraft identified in Tables 11 and 12 are not an exhaustive list, and many other unmanned aircraft options exist. With SUAS size, weight, power, payload, and environment resistance requirements, a long-endurance aircraft is not feasible with current battery and manufacturing technology [22]. Thus, assuming current SUAS capabilities, it is not feasible for a single SUAS system to enable persistent or widespread bandwidth access. Furthermore, at the current SUAS price points, it is not practical for individual organizations to purchase multiple systems [23, 24, 25]. Although SUAS payload capacity is limited, researchers have demonstrated that they can provide useful communication capability.

Previous research by the University of Colorado's Ad Hoc unmanned aerial vehicle (UAV) Ground Network (AUGNet) system demonstrated that small, mobile, airborne-based communication is possible [26]. AUGNet utilized a single dipole antenna that, along with IEEE 802.11's limitations, resulted in a high variance in packet drops. This made it difficult to establish a constant and reliable link. Current research by the University of California at San Diego has presented a functional Global System for Mobile Communications (GSM) implementation deployed on a small, airborne platform, called AirGSM [27]. The AirGSM's project goal is to develop a deployable GSM network that can seamlessly replace commercial service during an incident or disaster. Unlike AUGNet, AirGSM is not hindered by IEEE 802.11 unorganized shared-use, low-power radios. GSM, in contrast, is a managed spectrum, narrow-bandwidth system that leverages higher-transmission powers. AirGSM's system currently has limited range but could eventually be suitable for tactical communications.

Most current or proposed SUAS Concept of Operations (CONOPS) focus on reconnaissance, surveillance, and target acquisition [28, 29]. This aligns with traditional top prioritization roles of reconnaissance and precision target location and designation for military SUAS [30]. Currently, a CONOPS for SUAS to complement SatCom approaches has not been created, and moving forward, this capability gap must be addressed. This CONOPS needs to consider SUAS endurance and operational capabilities. The CONOPS should leverage the SUAS mobility to transmit essential information across a region. Additionally, communication payloads designed for SUAS should be a small enough size, weight, and power to allow it to be deployed as easily as other platforms, such as a deployable mast [31].

It is unlikely that a SUAS can act as a viable SatCom base station due to weight and power limitations. While persistent communications is not feasible, a "carry and store" concept is feasible. A SatCom base station can enable communications for a small tactical area. When available, a SUAS can be deployed containing essential or critical information. The SUAS could then travel to responders without SatCom connectivity and share information. If the airspace is unavailable, users can simply position the SUAS and communication payload on top of a building or mast to enable connectivity.

The CONOPS must also take into account aircraft data links and airspace regulations. Current UAS operations require a human-in-the-loop and are not completely autonomous. Therefore, the UAS must be controlled via a ground station. Ground stations range in size from a suitcase to a trailer. SUAS are controlled locally, usually with LOS operations, due to their small payload capacity. A key challenge is managing the data link spectrum and bandwidth [32]. If the aircraft is restricted by LOS operations, the communication capability will be affected. Besides the technical requirements to operate the aircraft, the CONOPS must abide by FAA regulations for airspace access.

In general, if there is an incident, there are a few paths to gain UAS airspace approval. The FAA has an *Emergency COA* process that can be used if an agency has an existing COA that can be leveraged for the emergency. For small UAS, this requires a ground spotter along with the UAS operator to deconflict the airspace. If the airspace is closed to civil traffic during the incident or disaster, such as with a forest fire, a responding agency is responsible. They separate visually or by rules (e.g., all UAS below 1,000 feet, helicopters at 1,000 to 2,000 feet, and firebombing aircraft only if they see the UAS). A similar concept was employed during Hurricane Katrina for manned aircraft.

## 6.3 DHS S&T-SPONSORED SMALL AIRBORNE COMMUNICATIONS PLATFORM

Infrastructure outages can be the result of natural disasters, bandwidth constraints, or the operating environment. During disasters, existing cellular or WiFi networks are often degraded or nonexistent. This creates a reliance on ad hoc networks. With organizations setting up their networks individually, it is difficult for different organizations to communicate directly with each other. This stifles collaboration. Additionally, existing airborne sensor and communication assets can be expensive and are often infrequently used by first responders. The lack of data sharing and communication infrastructure during disasters highlights the need for a communication system.

In response to this capability gap, DHS S&T sponsored MIT LL and The Pennsylvania State University (PSU) to design and fabricate a low-power, low-weight, reliable communication solution to provide essential information. The information from this section was published in *Providing Communication Capabilities During Disaster Response: Airborne Remote Communication (ARC) Platform* [31].

The airborne remote communication (ARC) system trades bandwidth for mobility and reliability. The ARC system is partly based on CubeSat technology. CubeSats are miniaturized satellites favored by academia and amateur radio satellite builders. The ARC system consists of the CubeSat communication technology, ground-based hardware and software components, and a platform on which the communication technology is deployed. It is data agnostic and can support a variety of data types, including GPS coordinates, SMS texts, or Emergency Data Exchange Language (EDXL) data.

The communication system described above consists of both hardware and software. Hardware includes antennas, the deployment platform, physical nodes, a power supply, radios, and transceivers. The software includes code architecture, encryption, the protocol stack, and the user interface. While the hardware and software inherently interact, this report primarily focuses on the development of the communication system's hardware.

Four components comprise the ARC system: the airborne platform, communication payload, ground station hardware, and system software. The airborne platform is responsible for housing the communication payload at a sufficient altitude for the desired aerial coverage. The ground station hardware is a fully-contained lightweight microcontroller that leverages USB "plug and play" to interface with existing hardware. The software component is data agnostic and responsible for transmitting information between units.

### 6.3.1 Airborne Platform

The airborne platform is responsible for the communication payload's deployment and addresses the requirement to support first responder communications in mobile environments. Airborne platforms can provide a mobile solution with rapid deployment capability. On such a platform, multiple antennas can be incorporated and antenna diversity employed. The platform could have numerous form factors, including an aircraft, balloon, or telescopic mast with corresponding trade-offs: an aircraft provides greater mobility whereas a balloon provides longer operational time. The ARC system can adapt to diverse operational requirements.

For this development cycle, the ARC system leveraged a radio-controlled high-wing aircraft, specifically the Senior Telemaster Plus (Figure 12). This aircraft has a 94-inch (239 cm) wingspan, flying weight of 9 pounds, and a payload volume of 5.86 × 3.39 × 6.50 inches (14.9 × 8.6 × 16.5 cm).

*Figure 12. ARC aerial platform: Senior Telemaster Plus*

### 6.3.2 Communication Payload

The communication payload is an adaptation from the CubeSat architecture developed at PSU. The system has undergone the full project life cycle—system concept, requirements capture, risk analysis, component selection, schematics capture, layout, assembly, testing, integration, and implementation—by students with guidance from faculty and industry advisors.

The communication payload acts as a mobile airborne repeater to provide a communication link between remote stations that may have no other means with which to relay vital information. The repeater functions similarly to an amateur radio repeater with a dedicated frequency for uplink and a slightly offset frequency for downlink. The data repeater broadcasts the sent data to all observed nodes within the coverage range. The repeater confirms packet validity, buffers the data in the microcontroller, and then retransmits the data without any modification or additional processing.

The radio is based on the Silicon Laboratories EZRadioPRO chipset and functions as a software-controlled system. The current setup utilizes the IEEE UHF amateur band (420 to 450 MHz), but simple modifications are possible to tune to the 760 to 800 MHz public safety band. Additional RF circuitry is populated to boost performance, including power amplifiers, low noise amplifiers, filters, transmit/receive (T/R) switches, and balun transformers. Table 13 provides the communication board configuration options.

**TABLE 13**

**Communication Board Configuration Options**

| | |
|---|---|
| **Modulation Options** | Gaussian Frequency Shift Keying (GFSK) |
| | Frequency Shift Keying (FSK) |
| | On–Off Keying (OOK) |
| **Throughput** | 1–128 Kbps |
| **Power Output** | 0.25–2.0 W |
| **Frequency** | 420–928 MHz |
| **Additional Options** | Cyclic Redundancy Check (CRC) |
| | Data Whitening |
| | Manchester Encoding |

The crossed-dipole configuration provides near-omnidirectional coverage while airborne using a simple antenna construction (see Figure 13). The antenna pattern was modeled using "Field Calculations for Bodies with Arbitrary Surface" (FEKO), a 3D electromagnetic field solver (Figure 14). The antenna was then tuned and characterized in PSU's anechoic chamber facilities for minimal voltage standing wave ratio (VSWR) and as near-to-omnidirectional performance as possible.

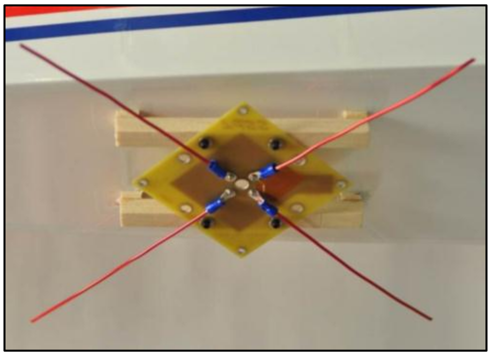


*Figure 13. Crossed-dipole antenna located beneath aerial platform's fuselage*

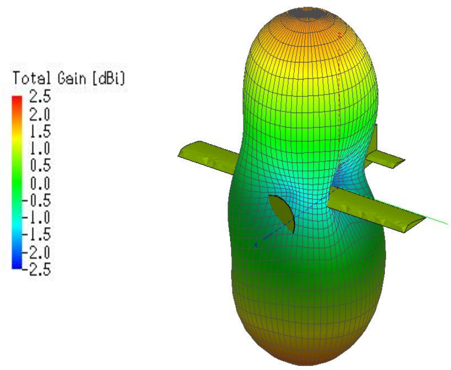



*Figure 14. FEKO simulation of crossed-dipole antenna attached to aircraft*

Based on the crossed-dipole configuration, the aerial repeater antenna is circularly polarized. This configuration results in a 3-decibel (dB) polarization loss when coupled with the use of a ground-station-based linear antenna, regardless of relative orientation. In comparison, if both transmit and receive antennas are linearly polarized, polarization mismatch losses could result in a complete loss of signal, depending on antenna orientation with respect to one another. The circular polarization, coupled with the linear polarization system configuration, is designed to facilitate the ease of use for first responders by not requiring specific antenna positioning for proper polarization matching.

Power for the payload is kept independent of the flight system for safety, reliability, and ease of testing. It is designed for integration with the aerial platform for single battery operation. Using a single battery reduces the complexity of the airborne payload. The system utilizes a Linear Technologies LT3510 step-down switching regulator for the 3.3 volt (V) and 5 V rails.

### 6.3.3 Ground Station Hardware

The ground station hardware provides the wireless interface necessary to connect to the airborne repeater. It consists of the same custom wireless modem and CubeSat communication technology as the airborne communication payload. The cost goal for the mobile station is between $300 and $500. Figure 15 provides an interface diagram for the mobile station.

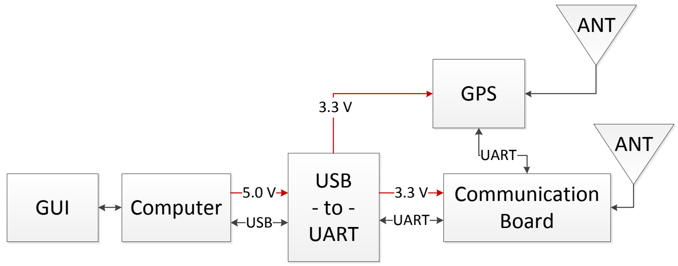



*Figure 15. ARC mobile station interface diagram illustrating the relationship between antennas, universal asynchronous receiver/transmitter (UART), GPS chip, communication board, and a computer with an external graphical user interface (GUI).*

Utilizing the same hardware as the aerial platform enables uniformity among all wireless components of the system, ultimately resulting in easier manufacturing, assembly, and system troubleshooting. Only minor firmware changes are required to reassign the role of the communications hardware from repeater to access node and vice versa.

The current hardware consists of the same radio board as the aerial platform with an additional USB interface for data and power from the host PC. The board is then placed in a ruggedized metal enclosure for durability and support with an external "rubber ducky" antenna (the type commonly found on portable radio receivers) for communication to and from the repeater, as well as an external patch antenna for GPS reception (see Figure 16).

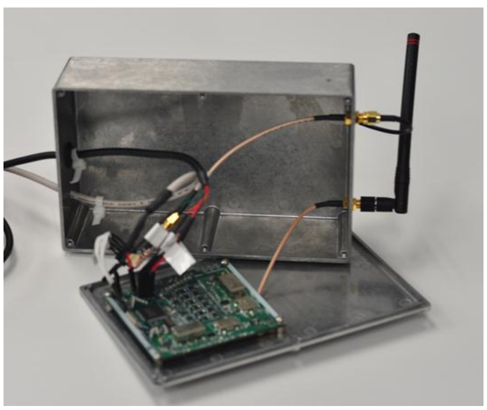


*Figure 16. ARC assembled mobile station box*

Transmissions sent and received from the mobile station are controlled via the system software on the host PC. Each mobile station node is uniquely addressable via the PC interface.

### 6.3.4 System Application Software

The system software is responsible for controlling the ARC platform. It has two primary functions: facilitating reliable communications and ensuring reliable, deterministic operation of the system.

The network stack (Figure 17) serves as the intermediate layer between the data and the transceiver radio. The network stack is a derivative of TCP/IP and uses all the built-in hardware functions provided by the transceiver radio. For this development cycle, the network stack contains packet segmentation and reassembly, CRC checksum with retransmission, up to 4 gigabytes (GB) maximum packet size, and support for 255 unique addresses within network with broadcasting.

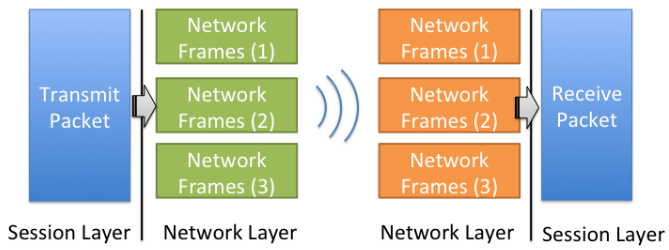



*Figure 17. Network transmission flowchart*

The software contains a central state machine that ties together the network stack, transceiver drivers, and data. The software contains built-in serial commands through the USB port to modify parameters such as power level, frequency, and addressing to change mission parameters during operation.

### 6.3.5 System Operating Environment

The ARC system can operate in rural and wooded environments and regions with low-to-medium population density. The current operating frequency provides adequate signal penetration across a large operating region. The system operations can range from environments such as post-Hurricane Katrina to high radio interference regions such as a sports event at a stadium. Deployment in an urban environment, such as New York City, is not ideal because of multipath propagation caused by densely-spaced tall buildings [33].

### *Link Budget*

Link budgets determine the operating range of the ARC system and take into account power, gains, and losses for a communication system; they calculate receive power, data throughput, or maximum transmission length. Attenuation caused by trees is a primary concern when calculating the theoretical operating range. Tree attenuation, calculated using the Goldhirsh and Vogel attenuation model, considers both the foliage and trunk (Goldhirsh and Vogel 2001). The baseline margin of 5 dB represents attenuation from propagation, fading, and other miscellaneous losses. The baseline assumes no tree attenuation. A moderately-treed condition introduces an added 10 dB of loss and a heavily foliaged environment is characterized by an additional 20 dB of loss due to trees.

The operational distance links were computed for three different frequency bands: Amateur Band (420–450 MHz), Public Safety Band (760–800 MHz), and the ISM Band (902–928 MHz). For the link budgets, the elevation was set to 1200 feet above ground level at an angle of 30 degrees. Table 14 summarizes the theoretical operating distance in miles for non-treed, moderately treed, and heavily foliaged operating environments.

The number of system users is limited by the amount of transmitted data. If nodes only send GPS coordinates, then more than 50 nodes can coexist with 4-second latency. Time division multiple access (TDMA) synchronization with 1 pulse per second GPS signal will also extend the amount of access points with further development.

**TABLE 14**

**Theoretical Operational Distance (miles) at 1200-feet Above Ground Level for Different Foliage Attenuations**

| Frequency (MHz) | No Trees | Moderately Treed | Heavily Treed |
|---|---|---|---|
| 420–450 | 17.7 | 5.5 | 1.8 |
| 760–800 | 9.3 | 3.0 | 1.0 |
| 902–928 | 8.0 | 2.5 | 0.8 |

### *Integration with First Responder Technology*

Rather than requiring users to deploy a separate ARC node in addition to existing equipment, users can communicate between ARC nodes using a gateway through an existing short-range standard communication protocol, such as WiFi. The gateway will use an ARC repeater to communicate with another gateway. By using a WiFi gateway, the system can link into existing networks without any hardware modification to existing laptops, personal digital assistants, tablets, or cell phones. This lowers the cost of the system and the operating complexity. The WiFi gateway will also allow the ARC system to potentially integrate with existing situational awareness tools [34].

#### 6.3.6 Comparison to Existing Technologies

This section describes other communication technologies and compares them to the ARC system. Other technologies include IEEE 802.11, IEEE 802.15.4, IEEE 802.16, cellular networks, SatCom, and aerostats. Primary differences between the systems are highlighted through transmit frequency, power, and the media access control (MAC). Transmit frequency and power are physical constraints that describe how the energy is propagated through the environment. The MAC is the protocol that manages channels and generally organizes transmissions. At a basic level, the MAC schedules when a node can transmit or receive.

IEEE 802.11 WiFi operates in the 2.4, 3.6, and 5.0 GHz frequency bands. WiFi operates at a similar power level to the ARC system (18 dBm [the power ratio in decibels of the measured power referenced to one milliwatt]); however; WiFi devices typically use antennas with lower gain, ranging from 0 to 2 dB, resulting in an approximate outdoor range of less than 1,000 feet (0.30 km). Additionally, due to WiFi protocols, data transfer and usability are significantly reduced at maximum range. Directional antennas can increase Wi-Fi range, but the narrower beam width makes it more difficult to establish the communication link due to pointing requirements [35]. Proprietary WiFi technologies exist that help mitigate the disadvantages of IEEE 802.11; however, 802.11's MAC is not designed for longer distance operations with many distributed users [36].

IEEE 802.15.4 operates in the 860 MHz, 900 MHz, and 2.4 GHz frequency bands. It is a low-cost, low-power WMN technology for low-rate wireless personal area networks. ZigBee, ISA 100.11a, WirelessHART, and MiWi are IEEE 802.15.4 implementations. The standard framework is intended for operations within 32 feet. The short range is a result of the MAC's low-duty cycle operations that enable energy savings at the expense of higher latency and lower bandwidth [37]. Although low cost and low power are advantageous, the extremely constrained range limits its applicability.

IEEE 802.16 operates in the 2.3, 2.5, and 3.5 GHz frequency bands and is commercialized as "WiMAX" [38]. It provides bandwidth up to 1 Gbps and operates at longer distances; however, this bandwidth is achieved using licensed spectrum and fixed-point, high-gain antennas. The reliance on tower infrastructure presents a significant risk of compromised communications during disaster events. Additionally, the use of fixed nodes drastically reduces the system's mobility. Similar to IEEE 802.16, cellular networks share the same infrastructure risk. Deployable cellular networks do not share this risk; however, they utilize proprietary software, have limited range, and lack scalability [39].

The ARC system provides a combination of mobility, low power, low cost, and connection reliability. Table 15 compares it to the IEEE standard technologies discussed above. Additionally, the ARC system is adaptable to future antenna designs for specific applications. The ARC computer transceivers can be tailored specifically to lower data rates to achieve a more stable long-distance link.

**TABLE 15**

**Communication Technologies Overview**

| Name | Frequency (MHz) | Bandwidth (Mbps) | Range (feet) |
|---|---|---|---|
| ARC | 420, 760 | 0.128 | 89,760 |
| 802.11 | 2400, 3600, 5000 | 54–108 | 1000 |
| 802.15.4 | 860, 900, 2400 | 0.250 | 32 |
| 802.16 | 2300, 2500, 3500 | 34–1000 | 163,680 |

The IEEE standards do not encompass all communication systems. In response, further research included aerostats, white-space communications, and CDMA450.

Limited mobility is inherent to small aperture terminals and communication payloads on high-altitude platforms such as an aerostat [40]. Communication payloads range from SatCom to cellular repeaters. An aerostat is an airborne system that remains aloft using aerostatic buoyancy; a moored balloon is an example. Both SatCom and aerostats are large and may be difficult to deploy rapidly, incur data costs, and require a large initial cost. Therefore, solutions using SatCom are often limited to organizations with larger resources. Recent research efforts have explored the use of smaller aerostats that can be deployed from a standard truck [15]. However, aerostats rely on power provided through a tether and still face mobility concerns. It is difficult to deploy a system without vehicle access. Additionally, it is difficult to ruggedize an aerostat for operations in extreme environments, such as a fire.

White-space communications leverage the unlicensed channels between TV channels. The future IEEE 802.22 standard will address these communications. These systems will operate similar to IEEE 802.11, but at lower frequencies and data throughput [41]. The lack of standard and available hardware introduces many risks. Additionally, these systems may leverage antennas not suitable for field deployment.

CDMA450 is a potential solution for rural data and voice connectivity. It leverages the CDMA2000 cellular standard with the 450 MHz frequency band [42]. Similar to ARC, it provides good LOS operations, leverages established technology, and has simple spectrum licensing. Although CDMA450 supports download speeds of Mbps and upload speeds of 12.4 Mbps, it achieves this at the expense of larger power requirements. CDMA450 requires large antennas and antenna spacing for reliable operations [43]. The initial cost for CDMA450 can be prohibitive for many first responder units.

### 6.3.7 System Evaluation

The ARC system was evaluated in two testing environments: a fixed tall antenna test to simulate airborne operations and a stadium test. Each test included the ARC repeater and ground nodes consisting of a laptop and ARC ground station.

The first test, from January 31 through February 5, 2012, consisted of the crossed-dipole, aerial repeater antenna mounted atop a 30-foot (9 m) pole located on the roof of a building approximately 120 feet (37 m) high. This scenario enabled the ARC repeater to operate approximately 150 feet (46 m) above the ground (see Figure 18). This test closely simulated the operation of the airborne platform in a moderately treed environment on PSU's park campus. Testing included the operation of five ground nodes situated around the campus and surrounding community as follows:

- Fixed node within LOS six miles (10 km) away
- Fixed node within LOS five miles (eight km) away through wooded area
- Fixed node inside a building
- Fixed node at the base of the repeater
- Mobile node moving around the building with repeater

*Figure 18. ARC test with repeater on mast atop a building (PSU's Dieke Building – middle) and mobile nodes located on Mt. Nittany (left) and at Pine Grove Mills, Pa. (right).*

The second test occurred on April 21, 2012, at Beaver Stadium on the morning of PSU's spring scrimmage ("Blue–White") football game. The ARC repeater was placed on the roof of the stadium's west press box, approximately 100 feet (30 m) above ground level. The communication repeater utilized a nearly-omnidirectional antenna with 2 dB gain. Testing included the operation of five ground nodes situated around the campus and surrounding community as follows:

- Fixed node within LOS seven miles (11 km) away
- Fixed node located in a wooded area beyond LOS five miles (eight km) away
- Fixed node inside a building
- Two mobile nodes moving around the stadium

During both tests, the ARC system enabled sharing of GPS coordinates between nodes, node-to-node text communication, communication through trees, and beyond LOS communications. This represented a data throughput of approximately 14 Kbps per node. These tests indicate that the ARC system can operate in the intended operating environment.

### 6.3.8 ARC Conclusions and Further Work

There is a need for a low-cost communication system for first responders and local emergency management. The ARC system meets this need by leveraging CubeSat technology to provide a small size, weight, and power solution at the expense of bandwidth. The communication system's hardware was successfully evaluated in an emergency management environment and enabled communications between nodes up to seven miles (11 km) from the repeater. Future research will focus on increased bandwidth, security considerations such as encryption, and operational constraints such as interference. To achieve this, development of a robust MAC that allows interoperability between first responders is required. We will also explore considerations for operations in the 700 MHz public safety band.

## 6.4 OTHER CELLULAR STANDARDS

The IEEE standards do not encompass all communication systems. In response, further research included white-space communications and CDMA450.

White-space communications leverage the unlicensed and unused primary channels between TV channels. The future IEEE 802.22 standard will address these communications as wireless regional area networks. These systems will operate similar to IEEE 802.11 but at lower frequencies and data throughput [41]. An 802.22 network consists of base stations and consumer premise equipment (CPE). CPE reports channel availability to the base stations, which then allocate channels to all CPE in their cells. Due to the reliance on channel reporting, the system's effectiveness to allocate channels is based on the ability to determine spectrum usage throughout the system [44]. The network’s reliance on dynamic channel allocation and potential fixed base station locations do not support disadvantaged communication scenarios well. Additionally, the current lack of standard software protocols and available hardware introduce many risks.

CDMA450 is a potential solution for rural data and voice connectivity. It leverages the CDMA2000 cellular standard with the 450 MHz frequency band [42]. It provides good LOS operations, leverages established technology, and has simple spectrum licensing. Although CDMA450 supports download speeds of 14.7 Mbps and upload speeds of 12.4 Mbps, it achieves this by requiring larger amounts of power. CDMA450 requires large antennas and antenna spacing for reliable operations [43]. The initial cost for CDMA450 can be prohibitive for many first responder units. The reliance on fixed infrastructure also puts the network at the same risks as existing 800 MHz cellular networks.

# 7. RECOMMENDATIONS AND CONCLUSION

This section will address practical considerations and strategies to understand the trade-offs of cost and capabilities. It will also address some best practices for sharing geospatial data and recommend areas for further research.

## 7.1 PURCHASING CONSIDERATIONS

When purchasing equipment for emergency data communications, it is important to keep in mind that the majority of the expenses will lie in data access. BGAN terminals are inexpensive, lightweight, and portable, but the data plans can be cost-prohibitive. VSATs often require a trailer mount and a generator, but the data plans are much more reasonable. The following sections detail the tradeoffs to consider and outline steps that can be taken to minimize data usage.

### 7.1.1 BGAN Terminals

BGAN terminals are relatively inexpensive to purchase, support both data and voice communications, are lightweight and portable, and are extremely easy to set up. Costs generally range from $1,500 to $5,000 for stationary devices and $5,000 to $15,000 for vehicle-mounted devices that can be used while in motion. Higher-end models include increased bandwidth capability, more than one phone port, and better weatherproofing. Typical bandwidth capabilities range from ~0.38 Mbps download and ~0.25 Mbps upload at the low end to a maximum of ~0.5 Mbps for both upload and download. Battery life for stationary devices is typically around 36 hours on standby and 1 to 3 hours of active use. Accessories such as extra batteries, AC/DC adapters, or solar charging panels can be purchased with many models.

Service plans and data rates for BGAN terminals tend to be extremely expensive. BGAN terminals transmit on the L-band frequency, which is a much longer wavelength than Ka- or Ku-bands typically used by dish terminals. The advantages of L-band include the ability to use a much smaller terminal than is required for shorter wavelengths, as well as offering better weather penetration. The major disadvantage is that both the terminals and the satellites used for L-band communications have a lower bandwidth, and therefore, a lower effective data rate. For a given area, all BGAN data traffic is routed through a single satellite, and that satellite supports a lower data rate than one used for VSAT communications; this places a premium on data routed through that satellite. For these reasons, BGAN is more costly from a provider perspective, which translates into significantly higher costs for end users compared to other options.

***Guide to Inmarsat Data Plans***

Service plans are typically sold in 3 to 24 month contracts and run from $79 (access only) to more than $6,000 (relatively generous data allowance) a month. Plans typically include a small amount of data (0–600 MB per month), voice communications (0–1,000 minutes), and charge overages from $4 to 13 per MB for data and $0.99 per minute for voice. Generally, the higher the upfront costs, the lower the cost/MB. Table 16 lists the charges that would incur from using 0 to 2 GB on the plans offered by three representative vendors for non-vehicle mounted BGAN terminals. Rates tend to be slightly higher for terminals that support operating while a vehicle is in motion.

**TABLE 16A**

**Sample of Subscription Stationary BGAN Terminal Plans**

| | | Cost | Included MB | Overages per MB |
|---|---|---|---|---|
| **Company 1**[*1] | **Plan 1** | $79 | 3 MB | $6.39 |
| | **Plan 2** | $119 | 20 MB | $6.29 |
| | **Plan 3** | $449 | 100 MB | $5.99 |
| | **Plan 4** | $2,749 | 750 MB | $4.99 |
| | **Plan 5** | $5,849 | 2 GB | $3.99 |
| **Company 2**[*2] | **Plan 1** | $49.99 | 0 MB | $12.99 |
| | **Plan 2** | $99.99 | 10 MB | $8.99 |
| | **Plan 3** | $299.99 | 50 MB | $7.99 |
| | **Plan 4** | $499.99 | 100 MB | $6.99 |
| | **Plan 5** | $1,999.99 | 600 MB | $5.99 |
| **Company 3**[*3] | **Plan 1** | $54.95 | 2.4 MB | $6.50 |
| | **Plan 2** | $125 | 21 MB | $6.71 |

[*1] Company 1 http://www.globalcomsatphone.com/bgan_service.html accessed on 4/3/13

[*2] Company 2 http://www.allroadsat.com/inmarsat-monthly-plans accessed on 4/3/13

[*3] Company 3 http://www.gmpcs-us.com/Inmarsat-BGAN-Airtime.htm accessed on 4/5/13

## TABLE 16B

## Charges by Usage for Subscription Stationary BGAN Terminal Plans

| | | 0 MB | 1 MB | 2 MB | 5 MB | 20 MB | 100 MB | 1 GB | 10 GB | 20 GB |
|---|---|---|---|---|---|---|---|---|---|---|
| **Company 1**[*1] | **Plan 1** | $79 | $79 | $79 | $92 | $189 | $699 | $6,603 | $65,493 | $130,930 |
| | **Plan 2** | $119 | $119 | $119 | $119 | $119 | $622 | $6,434 | $64,403 | $128,810 |
| | **Plan 3** | $449 | $449 | $449 | $449 | $449 | $449 | $5,984 | $61,188 | $122,530 |
| | **Plan 4** | $2,749 | $2,749 | $2,749 | $2,749 | $2,749 | $2,749 | $4,116 | $50,104 | $101,200 |
| | **Plan 5** | $5,849 | $5,849 | $5,849 | $5,861 | $5,920 | $6,240 | $9,927 | $46,700 | $87,556 |
| **Company 2**[*2] | **Plan 1** | $50 | $63 | $76 | $115 | $310 | $1,349 | $13,352 | $133,010 | $266,090 |
| | **Plan 2** | $100 | $100 | $100 | $100 | $190 | $909 | $9,216 | $92,068 | $184,130 |
| | **Plan 3** | $300 | $300 | $300 | $300 | $300 | $700 | $8,082 | $81,718 | $163,540 |
| | **Plan 4** | $500 | $500 | $500 | $500 | $500 | $500 | $6,958 | $71,379 | $142,960 |
| | **Plan 5** | $2,000 | $2,000 | $2,000 | $2,000 | $2,000 | $2,000 | $4,540 | $59,744 | $121,080 |
| **Company 3**[*3] | **Plan 1** | $55 | $55 | $55 | $72 | $169 | $689 | $6,695 | $66,599 | $133,160 |
| | **Plan 2** | $125 | $125 | $125 | $125 | $125 | $655 | $6,855 | $68,694 | $137,400 |

Quantities over $10,000 are in blue and quantities over $100,000 are in red.

[*1] Company 1: http://www.globalcomsatphone.com/bgan_service.html accessed on 4/3/13

[*2] Company 2: http://www.allroadsat.com/inmarsat-monthly-plans accessed on 4/3/13

[*3] Company 3: http://www.gmpcs-us.com/Inmarsat-BGAN-Airtime.htm accessed on 4/5/13

All plans are structured with a one-year agreement and a monthly fee. The monthly fee includes 1 to 20 MB of data and a certain number of voice minutes each month, and varying rates for each MB of data over the allowed amount.

Some vendors have publicized reduced rates for first responders. Two such plans are outlined below.

> Company 1[*1]: Access for one BGAN unit. $699/year, 24 MB included, $7 for each additional MB.
> Company 2[*2]: Access for up to 10 BGAN units. $2,505/year, 195 MB included, $6.68 additional MB.

Phone service for each is included at just under $1 per minute.

> [*1] Company 1: http://www.gmpcs-us.com/Inmarsat-BGAN-Airtime.htm accessed on 4/5/13
> [*2] Company 2: Quote obtained from Astrium Services 4/9/13

Many vendors also offer prepaid plans. Prepaid costs range from $0.70 to $10 per MB and can expire in as few as two months or as long as two years, depending on the vendor. Many also lump voice and data into a single bin. This means that using half of the allotted voice minutes decreases the allotted data amount by half, and using all of the allotted data means all voice calls will be charged as overages. Table 17 lists some of the prepaid options available. It should be noted that many services charge extra for streaming data (e.g., streaming music or video) from $5 to 25 a minute.

**TABLE 17**

**Sample of Prepaid Data Plans for Stationary BGAN Terminals**

| | | Cost | Included MB | Overages per MB |
|---|---|---|---|---|
| **Company 1**[*1] | **Option 1** | $139 | 20 MB | $6.99 |
| | **Option 2** | $274 | 40 MB | $6.99 |
| | **Option 3** | $405 | 60 MB | $6.99 |
| | **Option 4** | $520 | 80 MB | $6.99 |
| | **Option 5** | $640 | 100 MB | $6.99 |
| **Company 2**[*2] | **Option 1** | $95 | 11 MB or 100 min | None |
| | **Option 2** | $235 | 28 MB or 250 min | None |
| | **Option 3** | $465 | 55 MB or 500 min | None |
| | **Option 4** | $925 | 110 MB or 1000 min | None |
| | **Option 5** | $2,250 | 275 MB or 2500 min | None |

[*1] Company 1: http://www.globalcomsatphone.com/bgan_service.html accessed on 4/3/13

[*2] Company 2: http://www.gmpcs-us.com/Inmarsat-BGAN-Airtime.htm accessed on 4/5/13

To place these costs into perspective, Figure 19 illustrates the data required for common Web tasks.

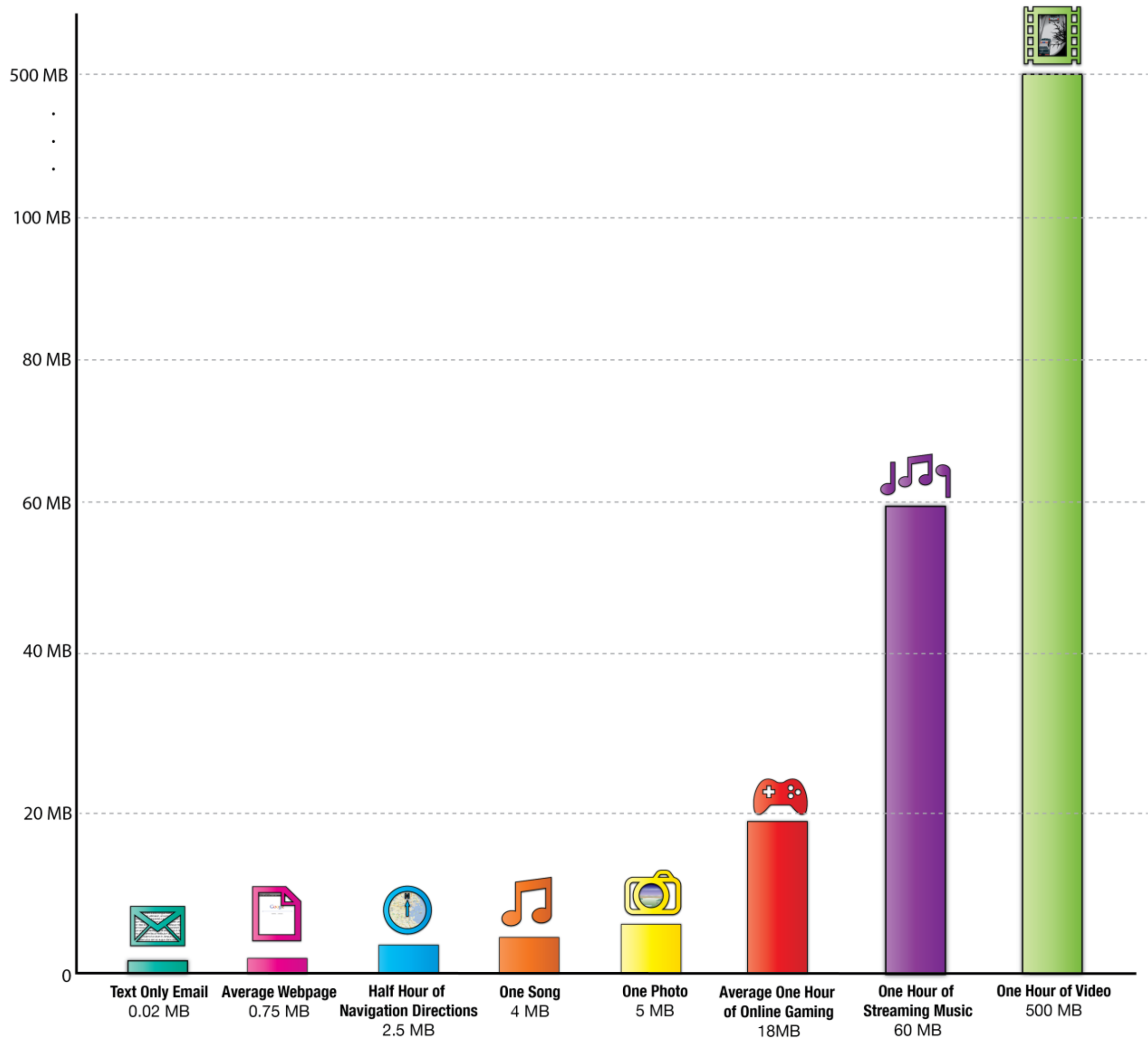



*Figure 19: Data usage by activity*

When using L-band communications, effective data management and eliminating unnecessary data usage is of utmost importance. Some data providers have data usage reduction software that utilizes compression and resampling techniques to reduce the amount of data transmitted. In addition, some programs allow the user to strip Web pages of ads or other nonessential information. Later sections will address some practical considerations for addressing unnecessary bandwidth usage in general and for GIS data specifically.

### 7.1.2 V-Sat Terminals

Satellite dishes are both more expensive and less portable than BGAN terminals, but the data rates are significantly higher and the data plans are significantly more affordable. The particular dish rented in support of this study had just been returned from supplying emergency communications in the wake of Hurricane Sandy, and the costs associated with rental and data access were in line with several other options investigated. It retails for approximately $30,000, weighs approximately 300 lbs., and generally must be mounted on a building or trailer. In addition, the dishes require access to electricity, generally via a generator. The system includes auto-pointing and does not require special training to set up or run. A more compact version, which may be mounted on a vehicle or placed on a flat surface, costs approximately $80,000. A system similar to the dish rented, but without auto-pointing, costs approximately $3,000. This is significantly cheaper, but, by law, an FCC-licensed individual must be present to point it correctly. FCC training takes approximately one day and costs approximately $200 per individual, but an organization purchasing such a system may want to ensure that several members of the team have such training. The data plan chosen supported 2048 KB download and 768 KB upload, and the cost of the data plan was $599 a month for 5 GB and $0.15 for each additional MB.

## 7.2 BANDWITH CONSIDERATIONS

As mentioned, effective data management and the elimination of unnecessary data usage are key to minimizing costs when accessing data through a satellite link. The following sections offer suggestions to reduce general as well as GIS-specific data accessed from the field.

### 7.2.1 Best Practices for Minimizing General Bandwidth Usage over a Satellite Link

- Turn off auto updating for all possible programs (e.g., Microsoft, Adobe, Java, most anti-virus programs) to ensure that these programs do not consume unnecessary bandwidth.
- Install a firewall application (one is included with Windows 7 and above; Zone Alarm is a well-reviewed third-party application) that will enable the user to be aware of which programs are accessing the Internet and block ones that are not vital.
- Minimize use of auto-refreshing websites.
- Disable automatic loading of images or videos when possible (e.g., in e-mail clients, certain webpages).
- Compress files and images whenever possible before transferring (e.g., by e-mail).

- Install bandwidth-monitoring software.
- If a wireless router is used, ensure that encryption is used in order to ensure no unauthorized users access the router. A whitelist that allows access only to specified computers is the safest way to ensure only known computers have access to wireless data.
- Take advantage of any optimization software offered by the service provider.
- Close Web browsers when not in use and turn off computers when not attended.
- Minimize use of high-bandwidth applications (e.g., streaming video/audio, high resolution uncompressed images).

### 7.2.2 Best Practices for Minimizing GIS Bandwidth Usage over a Satellite Link

The following section discusses several aspects of geospatial data that will affect system performance and user experience in limited resource environments. These aspects include geospatial imagery type and data location considerations. Additionally, common geospatial data collaboration platforms and how they can impact bandwidth requirements will be provided.

The type of geospatial data will affect the bandwidth required for data transfer. Two primary data types relevant to visual geospatial information are raster and vector imagery. Raster imagery consists of a matrix of individual pixel values and is the best method to store images with random content, such as aerial imagery (e.g., the satellite option in Google Maps). Raster images can be compressed using formats such as JPEG; however, they generally take up more space than vector imagery due to the random nature of the data. Raster imagery will suffer from blurring when zoomed past the intended image resolution. Vector imagery stores geometrical descriptions, such as points, lines, and polygons, of the underlying data; the streets view in Google Maps is an example of vector data. Vector images have the advantages that they are often smaller in size than raster images and can be zoomed in infinitely without a loss of feature definition. Also, vector data can be rendered on the server side or at the client, which has both processing and bandwidth implications. A server-rendered image puts the processing load of rendering on the server, while sending the raw vector data to the client requires the client to render the image. Transferring the raw vector data can reduce the bandwidth required depending on the number of features and geometry types. If the vector data consists of individual points, raw vector data will often require less bandwidth to transfer. However, if there are more complex geometry types including polygons with high point density, the raw data may be larger than a vector image.

Data location will also have an impact on bandwidth requirements for a collaboration system. Data that will be created and modified by several users will need to be stored in a commonly-accessible location where it can be quickly retrieved by users in other locations. Static data, however, is not bound by this restriction and can be stored in multiple places. Users who plan to have a low bandwidth connection to other collaborators and data servers could set up a source of static data on a higher bandwidth intranet (e.g., a field-deployable WiFi router). Static data sources could consist of many types of data, but the most common need in a geospatial data collaboration tool like NICS is the base map. The majority of data transferred for a NICS user is in the form of base map images. Therefore, if the base maps are stored locally on a high-speed intranet, or possibly even on each user's machine itself, the bandwidth requirements for geospatial collaboration are greatly reduced. This opens collaboration possibilities for users operating over very low bandwidth connections, such as SatCom or 3G cellular. Actual reductions in bandwidth used due to a locally-stored base map are difficult to quantify as each disaster response scenario has its own requirements for geospatial data to aid in decision making. However, most scenarios require a base map, and for those that require aerial (raster) imagery, local data access could reduce bandwidth requirements by an order of magnitude.

The choice of a geospatial platform can also influence bandwidth requirements. NICS, ESRI, and Google Earth all require equal bandwidth for displaying geospatial images using Open Geospatial Consortium (OGC) standards. Common examples of OGC standards are Web Map Service (WMS), Web Map Tile Service (WMTS), Web Feature Service (WFS), and Keyhole Markup Language (KML). There are several differences in the capabilities each software package has for allowing users to create, update, and delete geospatial features. NICS supports message-based transactions individually for each feature. A creation/update/deletion of a feature will results in a single message download by each other user. Google Earth does not support feature creation/update/deletion to a remote server. ESRI supports feature creation/update/deletion using Web Feature Service–Transactional (WFS-T). This protocol requires a user to query for all features in order to receive a change made to a single feature. This can result in an increase in required download bandwidth for other users proportional to the number of features that are being requested.

### 7.3 RECOMMENDATIONS FOR FURTHER RESEARCH

This study has identified several recommended areas for further investigation that may significantly improve overall performance, and therefore situational awareness for first responders. These include the following:

- Develop dynamic local software caching algorithms to minimize data sent over high-value network links such as SatCom.
- Develop data prioritization algorithms to allow systems to only send "essential" information over high-value network links such as SatCom.

- Develop medium- to large-scale node synchronization algorithms to efficiently resolve data merging across a large-scale deployed network. This would allow more data to reside "locally" during disaster events, while still providing a common data view for higher command.
- Develop locally-deployable hardware nodes to extend network connectivity, while minimizing the data sent over high-value network links such as SatCom (e.g., the ARC system described in Section 6.3).
- Develop intelligent, router-based algorithms to route traffic based upon near real-time understanding of the network topology, rather than relying on more standard TCP/IP, which has been shown to be suboptimal over SatCom.
- Build a suite of standard evaluation criteria, based on the work described herein, that other software systems and vendors can leverage to benchmark expected behavior.
- Conduct periodic "demonstration days" during which systems and vendors can perform system performance tests under common criteria. This information can be compiled and made available to the first responder community to inform their software and hardware decisions.

Ensuring reliable, efficient, and timely communication during a disaster and the ensuing response is an incredibly difficult problem with no single answer. However, when terrestrial infrastructure is damaged or unavailable, there are several reliable SatCom solutions available. These solutions introduce their own challenges, such as cost, but there are both hardware and software solutions available to help maximize the efficient use of the bandwidth available, thereby improving communications and minimizing overall cost. Furthermore, upfront care and consideration by first responders regarding the interoperability of hardware and software can greatly reduce the communication challenges faced when a large-scale disaster occurs.

# 8. LIST OF ACRONYMS AND ABBREVIATIONS

3GPP - 3rd Generation Partnership Project
4G LTE – 4th Generation Long Term Evolution
ARC - Airborne Remote Communication
AUGNet - Ad hoc UAV Ground Network
AirGSM - Air GSM
BD - Bandwidth-Delay
BGAN - Broadband Global Area Network
BSS - Broadcast Satellite Services
Bps - Bits per second
CDMA - Code Division Multiple Access
COA - Certificate Of Authorization
COMMEX - Communication Exercise
CONOPS – Concept of Operations
COTS - Commercial Off-The-Shelf
COW – Cell on Wheels
CPE - Consumer Premise Equipment
CRC - Cyclic Redundancy Check
DHS - The Department of Homeland Security
DSSS – Direct-Sequence Spread Spectrum
EDXL - Emergency Data Exchange Language
EOC – Emergency Operations Center
FAA - Federal Aviation Administration
FCC – Federal Communications Commission
FDMA - Frequency-Division Multiple Access
FEKO - Field Calculations for Bodies with Arbitrary Surface
FHSS - Frequency-Hopping Spread Spectrum
FSK - Frequency Shift Keying
FSS - Fixed Satellite Services
FirstNet - First Responder Network Authority
GB - Gigabyte
GEO - Geostationary Earth Orbit
GFSK - Gaussian Frequency Shift Keying
GHz - Gigahertz
GIS - Geographic Information Systems
GPS - Global Positioning System

GSM - Global System for Mobile Communications
GUI - Graphical User Interface
Gbps - Gigabit per second
HA/DR - Humanitarian Assistance / Disaster Response
HF - High Frequency
HFN - Hastily Formed Network
HSDPA - High Speed Downlink Packet Access
HSPA - High Speed Packet Access
HSPA+ - Evolved High Speed Packet Access
HSUPA - High Speed Uplink Packet Access
HTTP - Hypertext Transfer Protocol
ICS – Incident Command System
ICT – Information Communications Technology
IEC - International Electrotechnical Commission
IEEE - Institute of Electrical and Electronics Engineers
IETF - Internet Engineering Taskforce
IP - Ingress Protection
IPsec - Internet Protocol Security
ISA - International Society of Automation
ISL - Inter-Satellite Links
ISM – Industrial, Scientific, and Medical Band
JISCC - Joint Incident Site Communications Capability
KB - Kilobyte
KML - Keyhole Markup Language
LAN - Local Area Network
LEO - Low Earth Orbit
LL - Lincoln Laboratory
LMR – Land Mobile Radio
LOS - Line Of Sight
LTE – Long Term Evolution
MAC - Media Access Control
MEO - Medium Earth Orbit
MHz - Megahertz
MIMO – Multiple-Input and Multiple-Output
MIT - Massachusetts Institute of Technology
MSS - Mobile Satellite Services
NEMA - National Electrical Manufacturers Association
NG - National Guard

NICS – Next-Generation Incident Command System
NPS - Naval Postgraduate School
OFDM - Orthogonal Frequency-Division Multiplexing
OFDMA - Orthogonal Frequency-Division Multiple Access
OGC - Open Geospatial Consortium
OOK - On–Off Keying
PEP – Performance Enhancing Proxy
PSTN - Public Switch Telephone Network
PSU - The Pennsylvania State University
RF - Radio Frequency
RFC - Request for Comments
SC-FDMA - Single-Carrier FDMA
SC-FDMA - Single-Carrier Frequency-Division Multiple Access (FDMA)
SIM - Subscriber Identity Module
SOFDMA - Scalable Orthogonal Frequency-Division Multiple Access
SUAS - Small Unmanned Aircraft Systems
SatCom – Satellite Communications
TCP/IP – Transmission Control Protocol/Internet Protocol
TDMA - Time Division Multiple Access
U-NII – Unlicensed National Information Infrastructure
UART - Universal Asynchronous Receiver/Transmitter
UAV - Unmanned Aerial Vehicle
UDP – User Datagram Protocol
VSAT – Very Small Aperture Terminal
VSWR - Voltage Standing Wave Ratio
VTOL - Vertical Take-Off and Landing
VoIP - Voice over Internet Protocol
WCDMA - Wideband Code Division Multiple Access
WFS - Web Feature Service
WFS-T - Web Feature Service–Transactional
WLAN – Wireless Local Area Network
WMN – Wireless Mesh Network
WMS - Web Map Service
WMTS - Web Map Tile Service

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