Cost-Effective Solution for First Responder Communications and Situational Awareness

Capstone Research Project

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***Abstract*- Wildland firefighters sustain operational voice communications through the use of Land Mobile Radios (LMRs). The goal of this research project is to include, enhance, and incorporate instant messaging and situational awareness services. The concept of mobile instant messaging is well understood. Situational awareness, on the other hand, is the ability to identify, process, geolocate, and comprehend the critical elements of information about what is happening with regard to each operational firefighter, vehicle, and equipment relative to the fire. This research assumes that each firefighter is not only equipped with a handheld LMR but also will carry a personal smartphone. It will be shown that neither LMR nor cell radio coverage is necessary to support these added operational services and capabilities. The final product of this research and development (R&D) project is a combination of individual COTS hardware and a supporting android application. In the event, there is an available wireless network access point and associated backhaul, another end product is a server application that contains current and historic device tracking data and stores transmitted messages.**

***Index Terms*— Center of Excellence (CoE), First Responder, FirstNet, goTenna, LMR, Off-grid, System on Wheels (SOW), Situational Awareness, UAS.**

I. RESEARCH QUESTION AND PROBLEM SETTING

A. Statement of the Problem

Unavoidable disasters like forest fires, flash floods, and earthquakes endanger the public. A team of specially skilled operators, the First Responders, are called on to respond to such situations and to carry out the search and rescue operations.

Governments across the world have set up first responder organizations dedicated to different disaster scenarios. Communication between these officers is crucial and could be the difference between life and death. It has been a great concern for some federal agencies to have viable means of communications during emergency situations in forests such as forest fires and the search and rescue operations conducted by these firefighters. The difficulty in establishing communication depends on various factors including, but not limited to, topography and terrain. The use of voice broadcast in such situations limits the first responder's ability. Situational awareness is a critical aspect required to enhance the safety of the public and the first responders themselves. Situational awareness is the ability to identify, process, geolocate and to comprehend the critical elements of information concerning each firefighter, vehicle, equipment, and fire.

The question we are trying to solve is how to use an ad-hoc network system to extend cellular communications networks to improve situational awareness for wildland firefighters in all topographies. Various off-grid devices currently available on the market could be used to come up with a solution to improve the situational awareness of wildland firefighters.

The Colorado Center of Excellence for Advanced Technology Aerial Firefighting (CoE) from the Colorado Department of Public Safety were already conducting research in this area and expressed an interest in providing valuable data and resources for this project. The CoE previously performed a ground test with different commercial antennas [1]. The devices that their team identified for testing are the Very high frequency (VHF) voice radio, the 800 megahertz (MHz) voice radio, the goTenna off-grid device and the Silvus radio antenna. The report concluded that further testing would be conducted using the goTenna because of its various features and cost-effectiveness.

goTenna is a commercial off-grid device designed primarily for hikers and people who frequently travel to low-coverage mountainous terrains for recreational purposes. The goTenna used by the CoE in their experiment transmitted at the 151-154MHz frequency band, also known as the Multi-Use Radio System (MURS) band. Our team decided to collaborate with the CoE to develop a mobile app for goTenna which would have features that would assist the wildland firefighters on their rescue missions.

B. Research Problem

The wildland firefighters face harsh life-threating situations during forest fires. The current telecommunications technology available to the wildland firefighters is limited to only voice capabilities, and this limits the firefighter's ability to automatically and sufficiently transmit and receive essential information about his location or other mission-relevant data since LMRs are half-duplex devices. This delay in information transfer costs the firefighters crucial time as situational awareness information is only transmitted via voice. Advances in technology could provide them with all the necessary real-time information through high-bandwidth applications. Ad-hoc and backhaul networks are needed to enable communication in no-coverage areas. These ad-hoc and mesh communication networks allow wildland firefighters to provide text and GPS coordinates to each other and extend the communication network from the central operations to the first responders.

How to utilize off-grid devices to extend the communication network in order to improve situational awareness of wildland firefighters under different conditions?

II. RESEARCH SUB-PROBLEMS

A. Does the mobile app of the selected off-grid device perform the necessary tasks and forensics that are needed by the first responders?

The firefighting team is not solely made up of extensively trained firefighters but also includes many volunteers from the general population for certain rescue missions. Almost everybody in this team carries a cellular phone, and through discussions with the CoE researchers, we realized that the selected off-grid device should connect to a cell phone that every public safety user can have access to. The mobile application should have features that would help wildland firefighters while on the mission. The firefighters should be able to send and receive text messages, GPS coordinates, voice and other mission-related information from the rest of the team. The mobile app should also have the functionality of plotting the GPS coordinates on a map. Google Maps provides very accurate GPS location tracking and is widely used by various mobile apps. However, Google Maps requires a constant Internet connection for the app to function, unless the user downloads an off-line version of the map. The app that the team has developed already contains the offline maps, and the wildland firefighters would not have to download the map before any mission. The app should also transmit the coordinates automatically so that the wildland firefighters are not distracted from their mission by having to update the base station about their current location continuously. The app should also show the user his movements as well as that of the rest of the group.

Forensics is a key aspect of any public safety mission. Forensics would help the wildland firefighters with understanding the cause of injury/death of a fellow firefighter and would help with tracking down a missing firefighter. The mobile app must have the functionality to store all the messages and GPS locations of the wildland firefighters who are carrying the off-grid device. In case of an accident, the mobile app would be able to provide answers such as what messages they sent before the accident, whether anyone received those messages from the wildland firefighters, which path they took during the mission. Forensics would also help wildland firefighters during the search and rescue of a missing person. They can see the paths each one of them has taken on the map and analyze if they missed a region. The mobile app should have the functionality of storing the sent and the received messages and coordinates of the user in the cache memory of the app, as well as in the internal directory. This duplicate storage of data may seem highly redundant but is of extreme importance in the case of an erred deletion of the app or corruption of critical mission data.

The Colorado Center of Excellence’s Pilatus PC-12 Multi-Mission Aircraft (MMA) [2] is equipped with a state-of-the-art L-3 Wescam MX-15 motion imagery electro-optical/infrared (EO/IR) camera ball that takes highly detailed aerial shots of the location of the fire or any other area the wildland firefighters are currently deployed. These shots depict the potential hot-spots, fire range, recent fire developments and other aspects relevant to forest fires. However, there is no way to communicate this mission-critical information to the wildland firefighters on ground zero. Our app would try to provide a solution to solve this problem. To convey the information received from the Wescam of the MMA, the app should be able to select a specific area and send information about this field to the wildland firefighters.

B. Can a backhaul network be created so that an administration can remotely access the data on the Internet and communicate with the wildland firefighters?

A backhaul network is necessary for connecting the wildland firefighters to the main operations center, and it is imperative that there is a constant flow of information between these two teams. The center needs to know the exact locations of the wildland firefighters in the emergency situations so that they can create an action plan accordingly. Right now, if there is a fire in the mountains, the information is relayed to the Denver headquarters over voice. The main operations center is not aware of locations of the wildland firefighters. Thus, the off-grid device must have a functionality to send all its information to the Internet. An admin at the main operations center can then log into a secure web server and see the wildland firefighters' location.

Having a backhaul connection would permit the wildland firefighters to transmit mission-critical information to the main operations center. The team identified a System on Wheels

(SoW) as the equipment suitable for communication between the wildland firefighters and the backhaul network. This box has network interface cards that can provide the wildland firefighters with a 4G/LTE connection and also create a backhaul network thereby providing connectivity to the first responders. Not only will they be able to communicate via text and voice, but they would also be able to send large files containing mission-critical information.

Alternatively, Colorado CoE's MMA can provide a solution to this problem. The aircraft is equipped with an in-cabin Wi-Fi network that is linked to an aircell which provides internet connectivity and can link the main operations center to the wildland firefighters [3].

C. How does the entire system interact in different topographies?

The entire system, which is comprised of the off-grid device, its mobile app and the web server, should remain functional in all different scenarios. The goTenna connects to the phone and using the app on the phone, a wildland firefighter can communicate with fellow firefighters. If any phone has 3G/Wi-Fi connectivity, the app will upload all the stored messages and GPS locations onto the web server [see Figure 1].

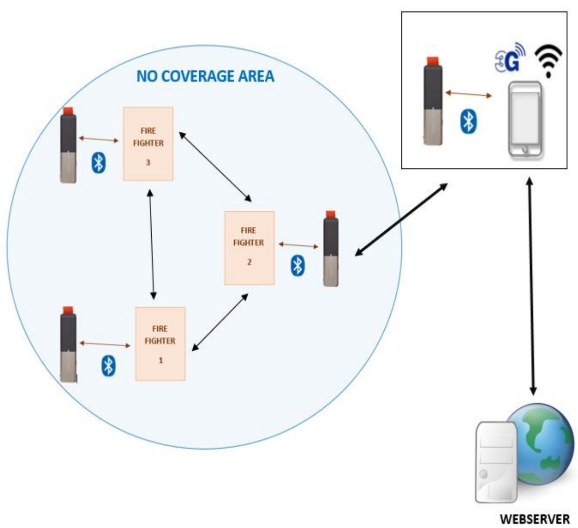


Figure 1. Working Design of the Network System

The situations in which wildland firefighters operate require zero margins of error. Any new system that is to be implemented must be tested thoroughly before making it available for use by wildland firefighters. The entire system must function in a way that wildland firefighters find it convenient and comfortable.

The system must work in different topographies that the wildland firefighters are most likely to work in. Topography is a major factor that affects the radio wave propagation. Radio signals can only be transmitted to distant regions if both transmitters and receivers are in line-of-sight of each other. The signal usually gets reflected by mountains, and hence, there is a weak network connectivity in the mountain region. The network coverage will be much better in the grasslands compared to the urban areas and mountainous regions. The wildland firefighters should be aware of how the spectrum will behave in different scenarios to plan the rescue operations accordingly.

D. Can an Unmanned Aircraft System (UAS) be integrated into the wildland firefighter situations?

The Line of Sight (LoS) is a type of radio propagation where the transmitting and receiving stations can view each other without any obstacle in between them. This propagation is the most efficient way for long-distance data communications as the signal does not suffer significant losses due to reflection or attenuation. However, wildland firefighters operate in dense forest terrains usually surrounded by mountains. These topographies limit the range of the system and hinder the communications between the firefighters.

Unmanned Aircraft Systems (UAS) provide a solution to this problem. Most of the commercial UASs can fly up to 400ft. If the transmitter is attached to the UAS and flown up to a certain height, LoS can be established between the two radio units, and this would greatly enhance the range of the communications system. UASs could also be used to collect information on wind conditions up close in real time by the firefighters near the ground zero.

III. LITERATURE REVIEW

A substantial part of the difficulty in establishing communication between the wildland firefighters is caused by topography, weather conditions and the distance from cellular towers. There have been many incidents around the globe in which the existing communications infrastructure is not capable of fulfilling the increasing user demand or is simply not available in areas that are topographically challenging. In this case, the ubiquitous mobile networks could be utilized to form independent ad-hoc networks to enable peer-to-peer communications where communications systems are not reliable enough or non-existent.

After a careful study of the literature and thorough understanding of the communication systems currently in use by the wildland firefighters, we noticed that wildland firefighters are still heavily relying on legacy devices like Walkie-Talkies, using Push to Talk communication [4][5][6]. Even though these systems provide low-bandwidth communication, it is not suitable enough to be used in today's scenario where excellent, uninterrupted communication between the wildland firefighters is crucial. Using such limited resources in dangerous situations costs emergency personnel crucial time. Apart from basic one-way communication and manual location mapping, no other information, like the exact GPS coordinates and automatic text messages for SOS situations can be conveyed to the main operations center.

Robots were initially thought of as a safe way of communicating during the initial stages of massive fires to increase the situational awareness by gathering useful information about the emergency situation that would greatly help firefighters make informed decisions about the best way to contain the fire. In extremely dangerous situations, it is risky for the firefighter to be in the hot zone and collect the required information needed to assess the situation and act accordingly.

During the firefighting operations, saving lives is the primary objective, and that is why a robot was determined as a potential solution that can be deployed during such situations [7].

In the past, computer software has been developed to help the firefighters by increasing their situational awareness. The Fire Management Information System (FISM) was one such tool designed to assist the firefighters. The chief objective of FISM is to act as a decision support system designed for fire prevention and fighting. FISM provides several functions related to monitoring fire-related conditions and real-time communications. FISM offered features such as weather monitoring, fire risk evaluation, and fire modeling and detection. Therefore, FISM works as a great tool in aiding firefighters, but it is an expensive service to be purchased, used and maintained by firefighters [8].

The First Responder Network Authority (FirstNet) is constructing a national public safety network based on the Long Term Evolution (LTE) technology, at 763-769 MHz/793-799 MHz [9]. The Smart Phone Ad-Hoc Networks (SPAN) project worked towards solving connectivity issues in smartphones by utilizing Mobile Ad-Hoc Networks (MANET) to provide a backup framework for communication between two smartphones when all other communication infrastructures are unavailable, overloaded or unreliable [10].

MANET is already widely used to address telecommunication challenges. Assuming that the wildland firefighters carry 802.11 compliant cell phones which support ad-hoc mode, this ad-hoc mode is suitable to set up MANET between a wide range of heterogeneous devices [11]. Using 802.11 compliant wireless devices allow the wildland firefighters to share photos, videos or other important situational awareness data, that requires high bandwidth. The major drawback of using a MANET for emergency situations is its low range and low penetrability. In cases where the area covered by the Search and Rescue team is large, they would lose connectivity and the communication between them would eventually be lost. Work has been done to solve this problem by using a low-frequency device, making use of its higher penetration capability. Off-grid devices operating on low frequencies have been developed to maintain the connectivity between wildland firefighters when the distance between them is too large to use high-frequency devices successfully [12].

Another problem faced during the deployment of MANET with multiple central nodes is handoffs. When multiple devices in the MANET are connected to one of the central nodes and when a device moves from one central node to another central node, handoff takes place, and as a result, the first connection is dropped to establish the new one. For seamless handoffs with slight or almost no loss of communication, Paul Chandra and J. Kahn have suggested solutions like handover queuing, finite state transducers and improved detection strategies [13][14].

Unmanned Aircraft Systems (UAS) have proven to be very useful in extending the communications network to address one of the problems that wildland firefighters face in the backcountry, that is the lack of communications means because of spotty or non-existent cellular coverage. UASs can make use of the nearby Wi-Fi access points or cellular tower to help wildland firefighters communicate with each other and access the Internet and its resources as well. UASs are also helpful in providing a reliable last connectivity that cannot be provided otherwise due to topographic irregularities. UASs could form a mesh-networked system to help extend the communications network by interconnectivity many UAS units [15].

Previous Interdisciplinary Telcom Program (ITP) graduate students at the University of Colorado at Boulder have researched into the possibility of extending the range of communication services for first responders in backcountry areas by using UASs. A part of the research looked into using UAS to identify buried avalanche victims using their LTE enabled phones [13]. In a subsequent study, students were able to test UASs with Wi-Fi payload to establish an ad hoc network to extend communication services [16].

The Colorado Center of Excellence conducted a ground radio test to determine which off-grid commercial device would be best to establish long-distance communications [1]. After the analysis, they discovered that the 800 MHz voice radio performs best at all distances. The goTenna was rated the second best, and there was no difference between sending text messages with or without locations attached. The goTenna performed flawlessly up to 9.6 miles. The VHF voice radio received the third-highest quality rating and received several ratings of partial reception. The Silvus radio presented the most complicated set of results as video streaming was not successful at all and file transfers were possible only up to 2.3 miles. After careful analysis done by the CoE, they decided that the best solution was to use goTenna as it is the cheapest option amongst these devices.

This project has plans to develop a solution with off-grid communications. These off-grid devices function independent of the communications infrastructure and can provide greater functionality for wildland firefighters during emergency situations when other communications means are not available. goTenna wireless units used in this project are an example of off-grid devices that can enable peer-to-peer communication while providing increased situational awareness for all users who use goTenna units. These units allow users to send a message and exchange their coordinates by preloading the maps into their smartphones. The project focuses on increasing the communications network of the wildland firefighters with the resources that are available to them. The app that the project develops will be focused on the needs of the wildland firefighters and will allow them to communicate information that they were not able to before.

IV. RESEARCH DESIGN AND METHODOLOGY

This research tries to solve the problem of creating a telecommunications network in remote off-grid areas. It seeks to enhance the situational awareness of the wildland firefighters by establishing an ad-hoc backhaul network. It attempts to discern how the frequency chosen for the ad-hoc networks would operate in various emergency scenarios.

The proposed methodologies for each sub-problem are as follows:

A. Does the mobile app of the selected off-grid device perform the necessary tasks and forensics that are needed by the wildland firefighters?

Methodology: Library and Market research, Industry Interviews, Field Testing

As the research question reflects, the primary purpose of the project is to improve the situational awareness of the wildland firefighters. The team has conducted market and library research about the solutions that would be helpful. Industry interviews with wildland firefighters revealed what functionality is crucial to the wildland firefighters. It also gave the team an idea of what might best assist in the wildland firefighter 'operations.

The solution that the team has built would assist the wildland firefighters significantly. The team has worked on a mobile application named goTenna Object and Access Tracker (GOAT) that connects the antenna to the phone via Bluetooth and gives the user a Graphical User Interface (GUI). The GUI would ease the work of the wildland firefighters. They would not need to read out their coordinates over the radio nor would they have to physically check their maps to see the location of the other users. The mobile application would work as a standard texting and GPS sharing app which would use the off-grid device network to transmit the data to the other user. The functionalities identified by the team after their research were:

- Send and receive text and GPS coordinates on the app
- Broadcast user's location every one minute
- Provide location tracking feature of the user
- Provide location tracking feature of the other users
- Send and receive polygons describing an area via the app
- Store all the messages and location for forensics
- Ability to log information to a remote web server if the mobile device has 3G/Wi-Fi connection

B. Can a backhaul network be created so that an administration can remotely access the data on the Internet and communicate with the wildland firefighters?

Methodology: Library and Market research, Field Testing

Even if wildland firefighters can communicate amongst each other, they are still disconnected from the central operations center. The constant exchange of information is crucial for the smooth and flawless execution of missions. The main operations center has critical information such as hotspot areas, evacuation areas, weather information and information about supplies that need to be conveyed to the wildland firefighters that are in action. The lack of communication between these two groups causes indecisiveness in the minds of the wildland firefighters and could lead to accidents. The wildland firefighter's location is critical to the main operations center. As per their location and their needs, the main operations center would be able to provide them with the required information and facilities.

This research project aims to rectify this lack of communication by creating a backhaul network that connects the wildland firefighters to the main operations center. The team interviewed people from the industry and the researchers present in the Telecommunications Program and the Aerospace department at CU about the proposed backhaul solutions and get their perspective about the discussed solution and alternatives. The team initially considered to integrate a System-on-Wheels (SOW) 4G/LTE box which will have a backhaul to the Internet. This 4G/LTE box has the function to provide a cellular network in areas where no network coverage is present. However, the SOW box is being developed by the National Institute of Standards and Technology's Public Safety Communications Research team. Certain policy issues were not addressed in time for the exchange of resources to happen between NIST and the University of Colorado Boulder.

Alternatively, the team has thought of using the Colorado Center of Excellence's MMA to operate as a backhaul network. The aircraft has Internet connectivity and could act as the link between the main operations center and wildland firefighters. The aircraft would also have the off-grid device and would receive the information from the wildland firefighters. Since the cell phone on the aircraft has Internet connectivity, the mobile app on it would transmit all the information to a web server whenever it has 3G/Wi-Fi connectivity.

The admin at the main operations center could then log into the web server and retrieve any necessary information from the database hosted on that server. This way, they would be able to see the location of the wildland firefighters on ground zero, as well as messages that were exchanged between them. By checking this information, they would have much more clarity on the current situation and could react to developments appropriately.

C. How does the entire system interact in different topographies?

Methodology: Industry Interviews, Field Testing

This project's main objective is to help the wildland firefighters in various emergency situations. Any object in the way of the radio waves attenuates and reduces the signal strength. Signal propagation differs according to the topography. For example, a grasslands environment would allow the signal to travel much farther than in concrete or mountainous environments. Whenever a new system is in development, it needs to be tested in different environments. The wildland firefighters need to be aware of how the system they are operating functions in different topographies. They need to know its limitations in the topographies they face.

The team tested the assembled system in different topographies. The assembled system consists of the off-grid device and a cell phone. There were different testing sites, and various wildland firefighter scenarios were tested on those sites. After interviews with our industry and faculty advisors, the following sites were chosen:

1. Concrete Environment (CU Boulder- Main Campus)
2. Mountainous Regions (Chautauqua Region)
3. Grasslands (CU Boulder-South Campus)

The system was tested in these three test sites to observe how much range the system can achieve without any loss of communication. We noted the distance until the communication between the two transmitting devices was completely lost. All the functionalities that the wildland firefighters would require were tested in these three test sites. We collected all the results and compared the three locations in detail in the results section of this paper.

D. Can an Unmanned Aircraft System (UAS) be integrated into the wildland firefighter situations?

Methodology: Library and Market research, Industry Interviews, Field Testing

As discussed before, UASs have the ability to enhance the range of the system with its ability to establish LoS. The advantages and applications of drones are increasing and the team believes that it will benefit the wildland firefighters in extending the range of the system. A thorough library and market research [16] [17] revealed that many organizations are using small cells or Wi-Fi transmitters on UASs to further communications in the backcountry where no-coverage areas exist. Prior research was also done by ITP students in this area and by talking to them, the team decided to integrate the UAS with our system.

The fourth test attempts to integrate a UAS into the system. The scenario that the team wanted to depict is that a wildland firefighter leaving the system's range. The group leader will mount his system on a drone and fly it to a certain height. The height advantage would give the system Line-of-Sight (LOS) ability hence, increasing the range.

V. RESEARCH RESULTS

A. Does the Mobile App of the selected off-grid device perform the necessary tasks and forensics that are needed by the wildland firefighters?

The goTenna device has a mobile app which does provide the users with texting and GPS functionality. However, it has been designed keeping in mind the needs of hikers rather than the wildland firefighters. Our team developed an app named GOAT using the public Software Development Kit (SDK) of the goTenna. We modeled the app around the needs of the wildland firefighters. We obtained the goTenna application SDK from GitHub. The goTenna website generated the app token, and we used this app token to connect the SDK to the goTenna device. We programmed the application in Java and modified it using the Android Studio. Several added features of the app make it unique and maximize the resources that the wildland firefighters have at their disposal. Since the app's main functionality is to function in no-coverage areas, we integrated offline Google Maps into the app storage. The app initially requires an Internet connection during installation, after which Internet is not needed for rendering the coordinates on the map. The app automatically broadcasts a user's location every minute. It may seem excessive and unnecessary, but the first responder may get separated from the group and wander out of the range of the ad-hoc network created by the off-grid device. The group would be able to check the last received coordinates from that user and would be able to locate that user [see Figure 2].

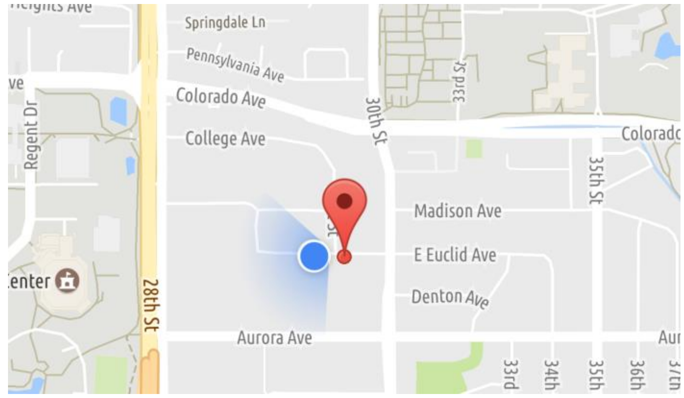


Figure 2. Received Coordinate Displayed on the Map

The app also provides the wildland firefighters with the ability to track all their movements on the map. They can see what path they have taken since the user started using the app [see Figure 3]. They can also see the paths of other firefighters as well. The app also gives the option to compare users' paths with each other. This comparison is of great significance to the wildland firefighters in search and rescue operations. The wildland firefighters would see all the paths that they have taken on the map and see if they missed an area that needs to be covered. This would assist them in efficiently completing their search operation.

Figure 3. User Path Displayed on the Map

As discussed earlier, the MMA's main functionality is to capture detailed, high-quality pictures of the fire from above with EO-IR imaging system. The image is processed and displayed on the screen of the operator with latitude and longitude grid. From this image, the operator can decide what areas interest them and what their significance is. They will then proceed to select the area using the touch screen on the map. They will create a polygon by selecting multiple coordinates on the map to represent that area. They will send this polygon to the first-responders on ground zero using the goTenna antenna. The message will be a .csv file with the coordinates in the correct order. On receiving these details, the receiving unit will plot the coordinates on the map and display a polygon to all the other users. [see Figure 4]. A text message with significant information about the displayed area would follow. Coordinate tracking and reporting are one of the most cost-effective solutions to use the Wescam's functionality in the no-coverage areas.

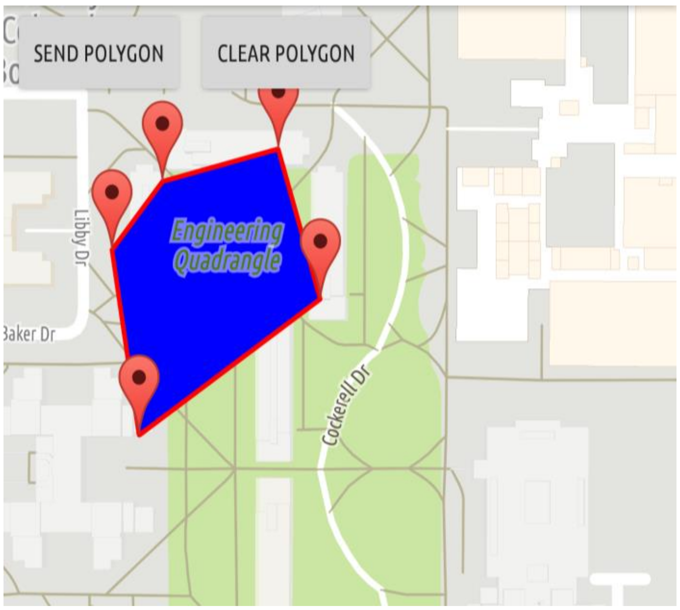


Figure 4. Polygon Displayed on the Receiver Side

B. Can a backhaul network be created so that an administration can remotely access the data on the Internet and communicate with the wildland firefighters?

The team firmly believes that the main operations center needs to be in constant touch with the wildland firefighters on the ground zero. This could have been easily done using the 4G/LTE System-on-Wheels box. However, it is an expensive piece of hardware and is not easy to deploy throughout the country. Additionally, only the large cities' wildland firefighters can afford such equipment. Unfortunately, the team was not able to get the necessary permissions to use this hardware for integration.

Hence, the team designed the app with the functionality of dumping all the messages and GPS data into a web server, whenever any cell device using goTenna gets 3G/Wi-Fi connection. The webserver provides a centralized control viewpoint for any person in command. On the web page, the team has added functionality of logging in, adding users, and seeing the location and forensic specifics of each user. Once logged in, the web server user would have the option to look at the list of all the users. From the list of all the users, one can select a single user and check his received and sent messages along with the time stamp and their last coordinates recorded. The coordinates recorded are plotted on a map, and one can look at the path traveled by wildland firefighter user [see Figure 5]. All the information presented in the web portal is stored in a MySQL database. The database has multiple tables such as a users table, messages table and a location coordinates table. The user's table consists of the columns userid, username, password and email. The locations table consists of locationid, username, longitude, latitude and timestamp. Similarly, the messages table consists of messageid, username, content of the message and the timestamp. Besides exchanging coordinates periodically with other users using broadcast messages, the app also dumps the coordinates and forensic details into the database using queries.

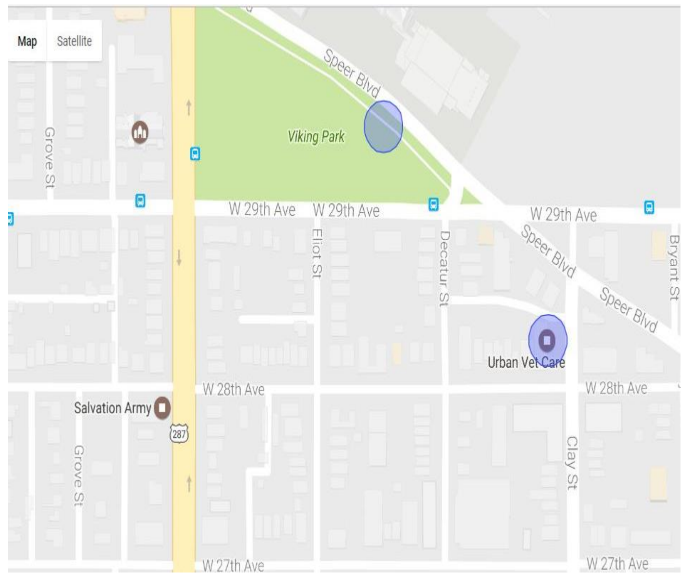
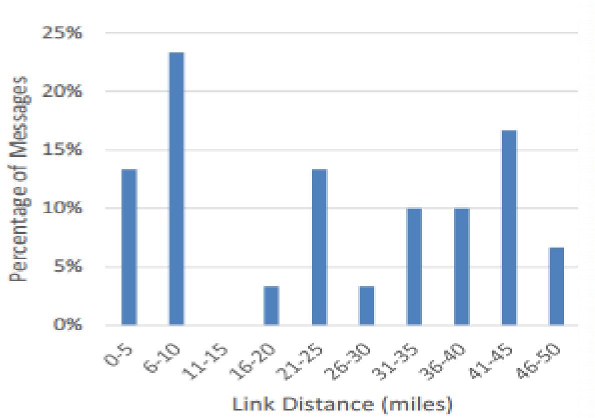


Figure 5. Coordinates Displayed on the Web Server

The Pilatus aircraft already has a goTenna device onboard and also has Internet connectivity. With its Internet connectivity, it can remain in touch with the main operations center. With the goTenna, it can correspond with the users on the ground. If the cell phone onboard the aircraft is connected to the goTenna, it will automatically dump all the information it has exchanged with the users on the ground zero to the web server. However, since the aircraft travels at such an altitude and speed, the team had doubts regarding whether the connection between the ground zero wildland firefighters and aircraft could be accomplished. Hence, the team along with the Colorado Center of Excellence conducted a proof-of-concept Air-to-Ground Link Test [3]. The CoE had recently obtained two goTenna Pros. It is a new version, which gives users ability to tune the frequency of the antenna. The testing was conducted on the 453.465 MHz frequency, allocated to wildland firefighters. The test was performed over the Eastern Plains of Colorado to take advantage of the quiet radio frequency environment, lack of terrain or forest canopy obstacles and to avoid congested airspace over the Front Range urban corridor. A ground party was stationed at exit 336 on Interstate 70, midway between the towns of Deer Trail and Agate. The ground party utilized a goTenna Pro prototype with an omnidirectional whip antenna and an Android tablet running the standard goTenna app. The aircraft arrived overhead at the ground party's location at an altitude of 15,000 feet above ground level and established a 5-mile orbit. Five identical 160-character text messages were transmitted from the MMA to the ground party and five from the ground party to the MMA. The testing radius was incremented after every successful exchange of five text messages.



Graph 1. Distribution of Messages by Distance [3]

The maximum link distance achieved during the test was 46.75 miles. Both testing parties reported that the radios rapidly transmitted messages with no failures over link distances of up to 40 miles. Hence, from the testing, it was established that the goTenna could be used from the aircraft to connect to the users on the ground. The goTenna user on the aircraft would receive the location of the all the wildland firefighters automatically. As the aircraft has Internet connectivity, it would provide the cell device with 3G connectivity. Since the app has a gateway to the web server, all the information saved as forensics will be transmitted, and the admin on the main operations center can log in and be updated regarding the locations of the wildland firefighters.

C. How does the entire system interact in different topographies?

The team conducted the testing of the system in the topographies identified in research design and methodology 3. The main objective of the test was to find the maximum distance that can be achieved before communication breaks down. Private messages between two users were continuously exchanged throughout the testing. To confirm the communication breakdown, ten private messages sent and all those must fail to establish the communications failure. The maximum distances that were achieved during various topographies have been listed below:

Site	Max. Distance Covered
CU-Boulder Main Campus	0.135 miles
Chautauqua Hiking Trail	0.823 miles
CU-Boulder South Campus	1.501 miles

Table 1. Maximum Distance Achieved in Different Topographies before Communication breaks

We will now look at the individual testing site and discuss the scenarios.

- **Test Site 1: CU-Boulder Main Campus**

In this site, the team wanted to see how the system would behave in a concrete environment. Concrete blocks and reflects the radio waves. Since the University has a very dense formation of buildings, we did not expect to get much distance. One team was set up at the entrance of Engineering Center (Lat: 40.005706667; Long: -105.26541999). The other team chose the route which would consist of a vast number of buildings. The team would exchange private messages between each other. The teams lost communication after covering just 0.137 miles. Neither text messages nor GPS messages were being sent across. The team also tested the system inside the building. One team was set up on the ground floor, while the other team went to the basement below. Some messages were failing, but still, communication was possible. However, when the team went down another floor, no communication was possible. All other functionalities of the app were also tested. In case of an earthquake, if a first responder gets caught under debris, the system would not function very well. The team concluded that the system is not very successful in concrete environments.

- **Test Site 2: Chautauqua Hiking Trail**

Our test at this site was one of the most critical testing scenarios as the system was designed especially for wildland firefighters who operate in these kinds of environments. Chautauqua Hiking Trail consists of grasslands, followed by forest cover and mountains. As usual, one team was set up at the parking lot of Chautauqua (Lat: 39.999675; Long: -105.282563333). The other team went on a hike. The constant flow of private messages was being exchanged in the grasslands portion of the trail. The system would fail to deliver 1-2 messages in the forest cover of the trail. However, most of the text and GPS messages would go across. Having higher elevation from the fixed location also helped the system in prolonging the communication. The team lost full connectivity after covering 0.823 miles and hiking past the Second Flatiron. All other functionalities of the app were also tested. The team was not able to send any text or GPS message across the mountain. However, the wildland firefighters are usually separated by a dense forest cover, not mountains. The test results were promising as the system met the requirements that a first responder requires in these conditions.

- **Test Site 3: CU-Boulder South Campus**

CU-Boulder South Campus has not been developed yet. It remains grassland and therefore provided an excellent opportunity to test the system. Grasslands is another topography wildland firefighters operate in. As usual, one team was set up at a fixed location (Lat: 39.97885; Long: -105.2333166667). The other team roamed away from the site regularly sending private messages until complete communication failure occurred. A few messages failed to go through around 0.765 miles. Complete failure of communication was established around 1.501 miles. The team was not able to send any text or GPS messages across at that point. All other functionalities of the app were also tested. The results were promising at this site as well.

D. Can an Unmanned Aircraft System (UAS) be integrated into the wildland firefighter situations?

As expected, the team had no communication across the mountain on testing site no. 2. Hence, the team collaborated with Leptron to use its UAS for tests in such a scenario. The team went to Leptron's Testing Facility in Golden and attached the payload to their RDASS drone. The goTenna and cell phone were tied to the drone with Velcro. The drone was placed on the testing facility (Lat: 39.795061; Long: -105.230246667). The testing facility had a hill on its range. The maximum altitude of the hill was around 124ft. The other team went to a site B, 0.559 miles exactly opposite to the hill and stationed there.

The app transmits GPS broadcast messages every minute, and hence the stationary team would wait for a GPS message. No communication was possible between the drone and the team at Site B. It was decided that the drone would fly to a height of 10ft and hover there for at least 2 minutes before incrementing 10ft more. It would keep incrementing until the communication has been achieved. The drone has a battery life of less than 20 minutes so it would have to be brought down in case it runs out of the battery before the test is completed. The team at site A was in constant touch with the team at site B via the phone and relayed the altitude that the drone was at and whether any communication was achieved or not. The first broadcast message was received by team B when the drone was at 40ft from the testing site A. Team B was able to send private messages to the drone as well at that height. The drone was taken to a height of 60ft before the team decided to decrease the increments to 5ft to test whether the communication was possible at 35ft as well. However, no communication was possible at that height. Only from 40ft above the testing facility site A was the communication taking place. The test results are very promising.

The team proposes that an Unmanned Aircraft System (UAS) would be of great help to wildland firefighters. If a wildland firefighter gets separated from the group and is out of the range of the system, one person from the group can attach his system to a drone and can fly it to a certain height. It would increase the line-of-sight of the system and would increase the range. It would be of great help in search and rescue operations as well.

VI. CONCLUSION AND FUTURE RESEARCH

By performing hands-on tests of our off-grid system, our research provides a baseline for later groups to pursue further investigation of improving the communication amongst the wildland firefighters in no-coverage areas. The team knew the limitations that the wildland firefighters face and set out to make basic communications between the wildland firefighters possible. The team identifies the basic communication like text messaging and situational awareness of one another. The maximum distances achieved by the system in different topographies match the expectations of the team. The wildland firefighters are not separated by a considerable distance, and that distance is completely within the range of our system.

The mobile app GOAT was able to accomplish all the functionalities it set out to achieve. These features are not limited to wildland firefighters but can help other first responders as well. Any first responder who must go into a no-coverage area can use our system to communicate during a mission. For example, Forest Rangers could use this app for communication during search and rescue missions as well.

The team wanted to integrate mesh networking into the system, but that was not possible due to Federal Communications Commission (FCC) regulations and hardware issues. The off-grid device goTenna operates at 151- 154 MHz frequency, also known as Multi-Use Radio System band. To avoid congestion at this band, the FCC has banned using store-and-forward on this band, implying the team could not implement mesh networking into the system. Mesh networking would have increased the range of the system. Also, this goTenna only uses a single unlicensed frequency band. There is not much traffic on this band. However, it is still open to the public and is vulnerable to congestion and performance issues. The upcoming goTenna Pro has the ability to transmit at any frequency as it has a tunable antenna. Since wildland firefighters are allotted frequency bands of their own, they can tune GoTenna Pro with their frequency band. Since the FCC does not regulate store-and-forward on frequencies used by first responders, mesh networking is possible on such bands. Future research should focus on the advanced goTenna Pro, which would allow the integration of mesh networking into the system.

The team also felt that the bandwidth issue was not resolved. In today's world, one should be able to send and receive bandwidth-hungry files such as the images from Pilatus aircraft without any trouble. The future groups should work on systems that help compress these files by reducing overhead in the messages or by using latest compression techniques.

The testing results from the Leptron Flight Test were crucial as they exhibit the application of a UAS system in first responder situations. So far the use of drones in first responder situations is not encouraged by the Federal Aviation Association (FAA) and FCC, but the results from this test raise a few questions regarding that stance. The results from the test back our previous group's conclusion of using UAS's employing small cells to increase interconnectivity in the backcountry and no-coverage areas.

Overall, our research indicates that off-grid devices such as goTenna could provide immense applicability in first responder situations. Since the FirstNet deployment would take more than five years to be fully functional, this system would act as a perfect stop-gap measure in allowing wildland firefighters to coordinate operations and, ultimately, save lives, in the absence of a fixed communication infrastructure.

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