Ad Hoc Routing for Rural Public Safety

Final Report

SAFECOM Program (DHS-06-ST-086-006)

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A report prepared for the

U.S. Department of Homeland Security

Science and Technology Directorate

Office for Interoperability and Compatibility

November 14, 2008

DISCLAIMER

ACKNOWLEDGEMENTS

The authors would like to thank the public safety officials of Hot Springs County Wyoming and the other public safety officials from Wyoming, Montana and elsewhere for their willingness to supply information necessary to complete this project.

The authors would also like to thank the staff and students from the Montana State University's Electrical and Computer Engineering Department, Computer Science Department, and Western Transportation Institute for their assistance on this project. Special thanks go to Dr. William Jameson, Ms. Leann Koon, Mr. Gary Schoep, Mr. Justin Krohn and Mr. Chad Bohannan, who all contributed significantly to this report and the project in general.

This material is based upon work supported by the U.S. Department of Homeland Security under Grant Award Number 2007-ST-086-000001.

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EXECUTIVE SUMMARY

Mobile Ad-Hoc Networking (MANET) technology shows promise for application to public safety data communication in both urban and rural areas. While the challenges are arguably greater in rural areas, particularly in regard to lack of infrastructure, MANET should be considered as a technology applied to assist in overcoming these challenges. For instance, in a situation in which backbone access is limited, MANET could be used to share and extend connectivity throughout the scene of an incident. In a situation in which backbone access is not available at all, MANET could be used to provide data communication within an incident, in the absence of infrastructure.

In this study, researchers from Montana State University's Computer Science and Electrical and Computer Engineering departments and the Western Transportation Institute teamed with the Hot Springs County Sheriff's Department from Wyoming to investigate how MANET could be applied to rural public safety. By engaging public safety officials as primary stakeholders throughout the study, the project team made a best effort to ensure that real needs would be documented, and associated requirements would be elicited to serve as necessary performance benchmarks.

Five scenarios were derived, based on actual events and stakeholder input, to serve as a representative test-suite under which MANET could be applied and tested. Scenarios were documented thoroughly to provide a basis for realistic incidents and situations. MANET technology was then assumed for application to subsets of these scenarios.

Several popular ad-hoc routing protocols, AODV and DSR, were tested within scenarios and against each other using OPNET. DSR was extended to support Quality of Service (QoS) requirements, resulting in a new protocol named QASR. In nearly all cases, QASR outperformed AODV and DSR, and demonstrated that QoS requirements could be satisfied in certain rural public safety applications. Obviously this result is dependent on network density, technology used (including frequency choice), and general bandwidth requirements.

A demonstration of MANET technology was conducted for Wyoming public safety officials to show its potential application. Wyoming's Wind River Canyon was selected as the site for the demonstration since it is remote and prone to incidents. A simulated landslide was used as an incident for which MANET technology could be used to track responder locations, to share photographs and video, and to facilitate whiteboard-based collaboration. In addition, a mobile command post was simulated to provide wide-area network connectivity to nodes local to the incident.

The results of this study demonstrate the potential for application of MANET to rural public safety. While the technology is not applicable in all situations, sufficient promise was shown to merit further related research and development.

1. INTRODUCTION

On February 28th, 2007, Montana State University was notified by the United States Department of Homeland Security that its proposal for opportunity # DHS-06-ST-086-006 had been funded. This opportunity, released by the Office for Interoperability and Compatibility's SAFECOM program, included a call for research on the application of Mobile Ad-Hoc Networking (MANET), among other topics, to public safety:

> *Mobile Ad Hoc Networking (MANET) is a broad area of research. Future wireless communications systems in public safety will take advantage of Internet Protocol (IP) based technology. Based on the natural hierarchy defined by the SoR, it is believed that there will be situations in which public safety first responders will operate either in the absence of fixed infrastructure, or find themselves in situations where their communications systems cannot penetrate an area within which they are operating. In either of these cases, the public safety community needs to be able to continue to operate in an ad hoc fashion and MANET is expected to help achieve this result.*
>
> *The Internet Engineering Task Force (IETF), Institute for Electrical and Electronics Engineers (IEEE), and private corporations are currently developing MANET protocols for a variety of uses, most of which are geared towards commercial use. The public safety community would benefit from making the best use of ongoing commercial work, but only to the extent that reliability, performance, and security do not suffer. For example, research into the ongoing commercial work could clarify several items:*
>
> *1) Does the commercial work have a suitable leverage point for public safety?*
>
> *2) Is the work occurring in a place where public safety could influence its priorities?*
>
> *Using the defined four-phase methodology, the goal of this technical area is the development of a standardized MANET routing protocol that meets all of the requirements stated in the SoR. It is preferred that the SAFECOM effort supplement an existing MANET effort in the IETF, IEEE, or other appropriate standards development organization. If there is no viable candidate, then an open standards based public safety oriented protocol is needed.*

This opportunity came to Montana State University in a somewhat unorthodox fashion. Dave Larson, undersheriff in Hot Springs County, Wyoming, learned about this funding opportunity in 2006. In addition to his many regular duties as undersheriff in a rural county, Dave is tasked with identifying funding opportunities to help supply equipment and services to his department. He thought this opportunity might be of benefit to public safety efforts in Hot Springs County. After looking for academic partners for collaboration in Wyoming and finding little interest, Dave turned to the College of Engineering at Montana State University (MSU). At MSU, researchers in the Electrical and Computer Engineering and Computer Science departments were already conducting research on MANET and other communication technologies, and the Western Transportation Institute (WTI) was tackling communication issues in general for application to rural public safety. After discussing this opportunity with Dave Larson, the project team was formed and proceeded to write a proposal.

The project team was well-suited to address this problem, and with the involvement of Hot Springs County, it came with a built-in set of stakeholders and a natural focus: rural public safety. Thus, the emphasis of this work is on the application of MANET to rural public safety.

On March 1st, 2007, MSU initiated work on the project, which subsequently closed on August 15th, 2008. Through a partnership with public safety officials in Hot Springs County, the research team at MSU has conducted research at a variety of levels. In order to assure that the work of this project would be grounded in reality, the project team interviewed stakeholders and documented needs, requirements and representative scenarios. These scenarios were then used in lab-based simulations to evaluate the performance of existing and enhanced MANET routing protocols. Finally, the project team conducted a live demonstration of MANET technology for public safety officials in Wyoming.

Although this project is now closed, the results of the study should not serve as the end of the discussion of the application of MANET technology to rural public safety. In general, great interest and enthusiasm was expressed by stakeholders in the potential for MANET to improve their services. Challenges were identified that may take years to resolve, including non-technical, institutional issues such as funding, interagency cooperation, and workforce development. However, our conclusion is that this technology is viable and of benefit for these stakeholders and the greater public safety community, rural and non-rural alike.

2. DOCUMENT PURPOSE AND GUIDE

This document serves as both a summary of the work conducted on this project and a compendium of deliverables, as listed in the original scope of work. A best attempt was made to present deliverables logically versus chronologically and versus the original order outlined in the scope. A map is provided in this section that matches deliverables identified in the original scope of work with sections of this report. Different members of the team contributed to different deliverables, and deliverables vary in terms of technical versus general content. Thus, information may be presented in multiple report sections, and presentation style and voice may vary from section to section.

For reference, the original scope and deliverables are presented in the following section, corresponding to the phases recommended in the original problem statement.

2.1. Original Scope and Deliverables

2.1.1. Phases

2.1.1.1. Education Phase

In the education phase, the project team will review the Statement of Requirements (SoR), determine an abstraction of the SoR requirements that can serve as a baseline for subsequent evaluation and analysis, and will identify the stakeholder group and related scenarios for Hot Springs County. Presenting the SoR and scenarios in the context of the Hot Springs County stakeholder group will ensure that subsequent research and development will be applicable to this group, which is representative of remote rural public safety entities around the country.

The education phase will be co-led by the MSU ECE and CS departments and the Western Transportation Institute. The Hot Springs Sheriff's department will provide assistance in mapping SoR requirements and scenarios to rural scenarios and will serve as lead representative of the Hot Springs County stakeholder group.

In the education phase, the project team will carry out the following tasks:

Review of SoR

The project team will carry out an in-depth examination of the Statement of Requirements for Public Safety Wireless Communications and Interoperability to determine the requirements that are most relevant to applications of Mobile Ad-Hoc Networking for public safety.

Establishment of "Notional Requirements"

The project team will establish an abstraction, or set of "notional requirements" that can serve as a baseline for defining system needs and requirements. This phase will be conducted with anticipation of meeting quality of service requirements under sparse network conditions, as would be likely in rural public safety conditions. A full suite of applications, as outlined in the SoR scenarios will be considered.

Identification of Stakeholders

The project team will identify stakeholders from Hot Springs County willing to participate and provide feedback in this phase of the project. Initial stakeholders include those who have submitted written or verbal support for this effort:

- The Hot Spring's Sheriff's Department,
- The Bureau of Indian Affairs,
- The Hot Springs County Fire District,
- Hot Springs County Search and Rescue,
- The Thermopolis Fire Department,
- The Thermopolis Police Department.

Other stakeholders representing local, state, federal and tribal interests will be invited for participation.

Identification of Scenarios

The project team will work with stakeholders from Hot Springs County to identify scenarios representative of communication operability and interoperability challenges. Those for which Mobile Ad-Hoc Networks might facilitate better communications will be given priority for this effort. Initial scenarios that have been identified by the Hot Springs Sheriff's Department include:

- Black Mountain Fire – Responders in proximity to each other, but on opposite sides of the mountain, were only able to communicate after positioning an officer on top of the mountain to relay voice messages.
- Wind River Canyon – Responders are unable to communicate from within the canyon without the use of multiple relays.
- Grass Creek – Responders to an incident at a hunting camp were unable to communicate outside the incident location and had to travel back and forth into communications range to coordinate subsequent response.
- Bureau of Indian Affairs Law Enforcement – There is no shared common frequency with BIA, so all communication must be relayed from mobile to dispatch to dispatch to mobile.
- Communications with Thermopolis Police Department – Due to lower powered radios on the police department's radios, it is not always possible for the sheriff's department to hear police department radio traffic.

This list will be expanded to include scenarios from other stakeholder agencies. Scenarios will be developed in a fashion similar to those presented in the SoR, with emphasis placed on data communications functionality.

Deliverables:

- Notional network routing requirements document

2.1.1.2. Discovery Phase

In the discovery phase the project team will work with stakeholders to examine potential alternatives and solutions to determine if they meet the needs of the public safety community.

Scenarios will play a key role in this phase, and will serve as benchmarks, in conjunction with the SoR, against which the alternatives and potential solutions will be compared in the analysis phase. Emphasized will be the special needs of rural public safety agencies, which are typically required to cover large, sparsely populated geographic areas with little fixed communications infrastructure and challenging terrain. These agencies often work with low staffing levels, may be volunteer organizations, and generally have low budgets.

The Western Transportation Institute (WTI) will lead the project team in conducting this effort. WTI is well-suited for this task and will serve as the "interface" between technical evaluation and development and the public safety stakeholder group from Hot Springs County. The Hot Springs County Sheriff's Department will serve as lead representative of the stakeholder group.

In the discovery phase, the project team will carry out the following tasks:

Identification of Alternatives and Potential Solutions (Routing Protocols for Mobile Ad-Hoc Networking)

The project team will identify alternatives and potential solutions. Included will be routing protocols, and treatment will be given to other aspects of the greater system. For instance, a hybrid system consisting of a microwave backbone at the JAN level and a mobile ad-hoc network at the IAN level might be a reasonable alternative and potential solution to the general problem of providing communication operability for the public safety stakeholders. Routing protocols will be presented in light of such potential solutions and in conjunction with the scenarios identified in the education phase.

The team will place particular emphasis on standards-based approaches and will carefully monitor and assess activities in the IETF MANET, Ad-Hoc Network Autoconfiguration (autoconf) and IP over IEEE 802.16 Networks (16ng) working groups. The team will carefully examine IETF RFCs and drafts. In this phase the team will send a representative to the IETF quarterly meeting to aid the discovery process.

Summary of Implications of Alternatives and Potential Solutions in Light of Scenarios

The project team will summarize the potential implications of alternatives and potential solutions in light of the scenarios identified in the evaluation phase. This summary will be presented to stakeholders in the following task for review and feedback. This summary will be aligned with functional requirements and associated definitions in the SoR to assure consistency and compliance with the SoR, particularly with the "notional requirements" formed in the education phase.

Stakeholder Review and Feedback on Implications

The project team will present the technical alternatives and solutions to stakeholders in the context of the scenarios identified in the evaluation phase. Evaluation will be facilitated through on site focus group meetings where the SoR requirements, associated scenarios, and alternatives and potential solutions will be presented and critiqued. The summary of implications of alternatives and potential solutions will be presented to stakeholders for each scenario. Feedback will be solicited in the form of dialogue/commentary as well as survey(s), where appropriate.

Summary of Stakeholder Review and Feedback

Feedback from stakeholders will be reviewed and summarized, and organized to correspond to the SoR and the "notional requirements" from the education phase.

Deliverables:

- Rural public safety needs assessment
- Solution alternatives for rural public safety networks report
- Recommendation of IETF MANET-related drafts and RFCs

2.1.1.3. Analysis Phase

In the analysis phase the team will draw on the results of the education and discovery phases and explore, in detail, the viability of emerging MANET protocols and underlying wireless technologies to meet the identified requirements. Use of standards-based approaches will be emphasized, and the team will carefully explore the activities of the Internet Engineering Task Force MANET working group, relevant IEEE 802.11 and 802.16 working groups, and industry-led groups such as the WiMAX forum. Although the task is primarily focused on routing in the network layer, wireless system solutions often require cross-layer approaches, as media access control (MAC layer) and power control (physical layer) as well as information and channel coding, compression, class of service and priority enforcement methods often involve information sharing between layers to yield optimal results.

A gap analysis will be a key outcome of this phase.

The phase will be led by the MSU CS and ECE departments, with emphasis on adopting existing protocols, or adapting existing protocols with minimum alteration or extension.

In the analysis phase, the project team will carry out the following tasks:

Review of Rural Public Safety Requirements in Light of Solutions and Alternatives

The products of the education and discovery phases will be reviewed to compare solutions, SoR notional requirements, and rural scenarios. A solutions review meeting will be collected to verify the findings of early analysis. A presentation will be used to summarize the rural scenarios, prospective solutions and SoR notional requirements.

Survey of Commercial Products and Standards

The project team will conduct a survey of commercial products and standards, and will compare findings with the SoR notional requirements. Commercial MANET products will be surveyed and an assessment of MANET routing protocols will be conducted. A report summarizing MANET commercial products and routing standards will be prepared.

Gap Analysis of Commercial Products and Standards Against Requirements

A gap analysis will be used to determine gaps between commercial products and routing standards. The missing components or weaknesses of current routing techniques will be identified through comparisons between the SoR concepts and features of the alternative approaches. The team will place particular attention on standard approaches and ideas that are under discussion in the IETF working groups. A team member will attend the quarterly IETF meeting to obtain an up to date view of the most current ad hoc network routing proposals. The gap analysis will be quantified by conducting exploratory experiments, through modeling and simulations, to identify the strengths and weaknesses of alternative protocols. This will be accomplished by capturing the key elements of public safety application scenarios in simple models, and then using a network simulation tool, such as OPNET_{TM} to conduct quantitative comparisons. Standard MANET routing protocols, including DSR and AODV are currently supported by OPNET [1], and the team will explore the feasibility of studying the behavior of other promising protocols using this framework. The outcome of this phase will be a list of features that must be added to several of the existing standard protocols to meet the SoR concepts, together with a recommendation of the most promising approach.

Deliverables:

- PowerPoint report summarizing rural scenarios and SoR notional requirements.
- MANET commercial products and routing standards report
- Gap analysis report

2.1.1.4. Development Phase

In the development phase the team will develop a standards-based routing protocol most suitable to meeting the Public Safety SoR. Modeling and simulation techniques will be used to verify that the extended protocol meets requirements. A proof-of-concept field demonstration will be conducted, in which the functionality of the specified protocol is implemented.

This phase will be led by the CS and ECE departments and strongly supported by WTI and the Hot Springs Sheriff's Office. In the development phase, the project team will carry out the following tasks:

Development of Extensions of a Standards-Based Protocol

The most-appropriate standards-based protocol will be selected as a foundation. Extensions to fill identified gaps will be specified, designed and implemented. A MANET routing protocol design document will be developed to document the resulting extensions.

Validation of Extended Protocol Using Simulation

The extended protocol will be validated using large-scale simulation. An OPNET-based model [1] capturing system of systems architecture, using standard routing protocol, will be implemented. Simulations based on rural public safety scenarios will be used to validate protocol performance. Results will be documented in a report.

Implementation of the Extended Protocol

The extended protocol will be implemented on a Windows-based system. The protocol will be implemented as a virtual network adapter that can be downloaded to a Windows-based host as a driver. It will be fully compatible with the existing IP stack in the Windows and will be adaptive to different physical layers such as 802.11 and 802.16.

Proof-of-Concept Field Demonstration

The project team will conduct a proof of concept field demonstration, implementing the functionality of the selected approach through emulation using existing off-the-shelf hardware with minimal specialized software. WTI and the Hot Springs Sheriff's office will conduct this field demonstration to validate that the concepts meet the Public Safety SoR goals.

Software will be developed to demonstrate several prospective data, voice, video and image applications. The demonstration will be conducted for viewing by public safety officials, and feedback will be solicited for evaluation purposes. This validation step will offer substantial feedback to developers by providing an opportunity for public safety practitioners to test the protocols in a small-scale field environment.

Software will be installed on hardware representative of that already used by Hot Springs County public safety officials, particularly rugged mobile data terminals. The demonstration will be conducted for viewing by public safety officials, and feedback will be solicited for evaluation purposes. This validation step will offer substantial feedback to developers by providing an opportunity for public safety practitioners to test the protocols in a small-scale field environment.

Project Final Report

A project final report will be written to document the process and products of the project. In addition, the protocol requirements summary will be completed in conjunction with the final report.

Deliverables:

- MANET routing protocol design document
- Report documenting OPNET model and protocol evaluation
- Proof-of-concept demonstration design and experiment plan report
- Report document results of proof of concept demonstration
- Project final report
- Protocol requirements summary document

2.2. Mapping of Deliverables to Final Report

The following table maps deliverables from the original scope to the contents of this report:

Table 1: Mapping of Deliverables to Final Report

Deliverable	Location in Report (Section and Title)
Education Phase	
Notional network routing requirements document.	*Section 6, Notional Network Routing Requirements*
Discovery Phase	
Rural public safety needs assessment	*Section 3, Rural Public Safety Needs Assessment*
Solution alternatives for rural public safety networks report	*Section 7, MANET Commercial Standards, Routing Protocols and Gap Analysis*
Recommendation of IETF MANET-related drafts and RFCs	*Section 12.2, Recommendations Regarding IETF*
Analysis Phase	
PowerPoint report summarizing rural scenarios and SoR notional requirements.	*Section 4, Scenarios; Section 6 Notional Network Routing Requirements*
MANET commercial products and routing standards report	*Section 7, MANET Commercial Standards, Routing Protocols and Gap Analysis*
Gap analysis report	*Section 7, MANET Commercial Standards, Routing Protocols and Gap Analysis*
Development Phase	
MANET routing protocol design document	*Section 8, Protocol Design*
Report documenting OPNET model and protocol evaluation	*Section 9, Protocol Evaluation*
Proof-of-concept demonstration design and experiment plan report	*Section 10, Demonstration* Design
Report document results of proof of concept demonstration.	*Section 11, Demonstration Results*
Project final report	*(This entire document.)*
Protocol requirements summary document	*Section 8, Protocol Design*

2.3. Comments on Deliverables

The project team made a best effort to complete all deliverables, as proposed in the original scope. It was necessary to adjust the timeline to accommodate unforeseen changes and challenges. For instance, it took far longer to document real scenarios than was originally anticipated. In general, detailed incident and situation information was rarely readily available, and required extensive research, interviews and follow-up. Further detail is provided in *Section 4, Scenarios*. As a result, it was necessary to use an iterative process through the duration of the project to assess needs and requirements, and to define the specific scenarios that were used for protocol simulation and evaluation. Similarly, it was determined that participation in IETF proceedings was premature within this scope. Upon conclusion of this project, the project team believes that it would be appropriate to proceed with IETF for the purpose of protocol standardization. However, that work remains a topic for future discussion, and further prerequisite work may be necessary. With these and several similar qualifications, we believe that we have fulfilled all of our obligations as described in the original scope, with this final report serving as the principal deliverable.

3. RURAL PUBLIC SAFETY NEEDS ASSESSMENT

3.1. Introduction

At the core of this project are the needs of rural public safety agencies and the individuals who provide public safety services to residents of and visitors to rural areas. Hot Springs County, Wyoming, provided the perfect setting for assessing such needs.

As of 2003, the population of Hot Springs County was 4,665. Covering just over 2,000 square miles, Hot Springs County has a population density of barely 2.3 people per square mile. Two primary roadways cross Hot Springs County and intersect at the County Seat, Thermopolis, to form a fork: Wyoming Route 120, which runs from Thermopolis to the Northwest and towards Cody; and US 20, which runs through Thermopolis and the county from North to South (see Figure 1). Hot Springs County includes parts of both the Wind River Indian Reservation and the Shoshone National Forest; therefore, there are a number of local, state and federal government agencies that have jurisdiction over various areas of the county. The Wind River Canyon, to the south of Thermopolis along US 20, is particularly problematic in terms of communication. Canyon walls reach heights of more than 1,000 feet above the canyon floor and road below [2].

Figure 1: Hot Springs County, Wyoming

3.2. A Representative Example—Black Mountain Fire

Scenarios were used as the basis for research on this project. Further scenarios are presented in this report. One such scenario, the Black Mountain Fire, is representative of the challenges faced by rural public safety officials in Hot Spring County.

In 2004, a grass fire was called in to the Thermopolis, Wyoming dispatch office. The fire was started by lightning at Black Mountain, an area in eastern Hot Springs County 30 miles by roadway from the county seat of Thermopolis.

A narrative of the event is given by Dave Larson, Hot Springs County Sherriff deputy.

On a summer day there was a fire page for a grass fire at Black Mountain. Black Mountain is about 30 miles northeast from Thermopolis by roadway. Two deputies responded to the fire along with five fire trucks. Knowing the area, we were cognizant of the oil field that is on the mountain itself and the dangers that may arise if the fire was endangering the wells, pipelines, oil storage units and buildings that contain chemicals.

Both deputies arrived at about the same time to the general location. We were on a large hill just west of the mountain and could see the area of fire on the west slope. The fire was in the oilfield but there were no assets that were in danger at that time. Our response time was about twenty minutes from the page traveling about twenty miles of black top and about eight miles of gravel. About ten minutes after our arrival the fire trucks were making it to our location.

I stayed at the first location and the second deputy, also a fireman, responded to the scene of the fire with the trucks. There was a slight breeze from west to east pushing the fire up the side of the mountain. Travel on the mountain was made easier with the oilfield roads leading to the wells scattered on all sides of the mountain. The water tanker positioned out of harm's way while the other trucks went into the smoke and started fighting the fire.

After a short time I saw two trucks make it to the east side of the mountain, out of view from me now. The other deputy was catching little radio traffic from the firemen on the east side. They were talking but it was not clear what they were saying. The deputy placed his patrol truck on the crest of the slopes and relayed information from the east side to the guys on the west side. The east side of the fire was moving rapidly to the south and up the slope of the mountain to the west. The deputy, making things safer by providing radio communication to all the firemen, put himself in harm's way by the approaching fire lines from both sides of the mountain.

The major part of the fire was put out in about two hours. I left the scene when the fire was about out. The other deputy remained at the scene to relay radio traffic until the east side was out. Firemen remained on the scene for about six hours total mopping up the hot spots so the flames did not start up again. No oilfield assets were lost.

This incident is a good example of the rural public safety situation in rural Wyoming. The responders were from varied groups and many were contacted by a simple device—consumer grade pagers. There were multiple jurisdictions at the incident and some responders had multiple roles at the incident such as the sheriff deputy who was also a fireman.

Most importantly this incident shows the need for flexible communication systems. One deputy put himself in the path of the fire to relay communications. Although not in the narrative, the sheriff deputies also relayed communication between fire units and dispatch.

No responder should rely on a system that requires risk to establish basic communications. And as a practical manner, there are usually not enough responders at incidents in rural areas to afford to have someone act as solely a communication node.

It should also be noted that the fire department that responded was partially made up of volunteers. Volunteers make up large portions of responders in rural areas in fire departments and even emergency medical services.

3.3. Project Meeting with Stakeholders

Interviews with stakeholders from Hot Springs County and other nearby jurisdictions were also used to assess rural needs.

A stakeholder meeting for the local responder community was conducted on April 16, 2007, in Thermopolis. The meeting generated much interest and personnel from many agencies, including some state agencies, attended.

3.3.1. Attendees

Agencies represented at the stakeholder meeting include:

- Thermopolis Fire Department
- Thermopolis Police Department
- U.S. Forest Service
- Hot Springs County Ambulance
- Bureau of Land Management
- Bureau of Indian Affairs—Wind River Police Department
- Wyoming Public Safety Communications commission
- Big Horn County Sheriff's Office
- Hot Springs County Sheriff's Office
- Washakie County Sheriff's Office
- Worland Fire Protection District
- Wyoming Department of Transportation

3.3.2. Comment Highlights

The group's diverse background enabled dialogue on a wide breadth of needs and experiences. [A number of comments are categorized and addressed in Section *3.5, Rural Communication Needs*]

A system that is easy to use, portable and rugged, and inexpensive enough for a rural area or county to be able to adequately equip *all* of its personnel, many of whom may be volunteers, are needs that met with general consensus. Responders cannot afford the time for "one more thing to do" or to take a vehicle out of an incident to act as a communication relay.

Both voice and data communications between different agencies were recognized as significant challenges by almost every stakeholder at some point in the meeting. One agency often does not have the manpower to adequately cover an incident and many incidents involve a number of different jurisdictions just by nature of their size (in the case, say, of a fire) and location. The need for on-site communication capability and real-time data or video also was discussed on several occasions. "Simple photos" needed "now" of an incident scene, the location and surrounding terrain, or a missing person or suspect were mentioned. Current weather information, license and registration checks at traffic stops, the ability to call for back-up, asset locations, or floor plans of a building during a bomb scare were all mentioned.

3.4. Mesh Technology Demonstration

The proof-of-concept demonstration of mobile ad-hoc networks as applied to rural transportation operations and incident response was conducted on August 14, 2008. The demonstration was held in the Wind River Canyon in Hot Springs County about eight miles south of Thermopolis. The group in attendance was diverse in regard to representation/agency and responsibility, but every job represented included duties involving rural areas. Fourteen individuals from Thermopolis, Basin, Shoshoni, Cheyenne, and Fort Washakie, Wyoming, attended the three-hour demonstration and networking event.

Several individuals arrived early and the extra time allowed them to network and discuss the project, the technology, and needs of rural transportation, law enforcement, and public safety personnel. The demonstration began with introductions and a welcome by David Larson, Under Sheriff for Hot Springs County, and partner for the project. A brief overview of the project was given, including how it came to fruition and its relevance to Hot Springs County and the surrounding area. It was emphasized that this is a research project. The concepts involving rural versus urban applications along with data versus voice communications were conveyed. This was followed by a short presentation on mesh networks and the associated technology to be demonstrated. [Further information on the demonstration can be found in *Section 10, Demonstration* Design *and Section 11, Demonstration Results*.]

3.4.1. Attendees

Agencies represented at the demonstration:

- Big Horn County Sheriff's Office
- Boysen State Park
- Federal Bureau of Investigation
- Hot Springs County Fire Department
- Hot Springs County Sheriff's Office
- Tribal Law Enforcement
- Shoshoni Police Department
- Wyoming Department of Transportation

Job titles of those attending included police department chief, deputy fire warden, sheriff, under sheriff, deputy sheriff, sheriff's department captain, investigator, fire warden, deputy fire warden, assistant superintendent, communications supervisor, engineer, and program manager.

3.4.2. Comment Highlights

Ease of use was again stressed on numerous occasions, with the idea that the network be self-forming and self-healing and a responder could just "flip a button and form a network." Interoperability was also discussed throughout the demonstration. The concept that a data communications network could be formed easily and different agencies could communicate without difficulty, all with “no fiddling,” was appealing to many of the responders in attendance and repeated several times. One individual commented on the need to think outside the box when approaching communication challenges during regular operations as well as incidents. He further elaborated by suggesting that, particularly in his position, to “make your car your office” would be of benefit.

During the demonstration, attendees were asked about the applicability of the technology. A number of different uses were suggested. A representative of Boysen State Park asked about utility on a boat or buoy, which was notable because most discussion concerning incident communications dealt with terrestrial applications. It was further indicated that if “it was something useful, the technology will catch on.” Concerns about funding were again brought forth. Other sponsorships for grants were briefly discussed and a general consensus reached that partnerships were both valuable and critical to technology enhancements to improve rural public safety communications. Many comments gathered in conjunction with the demonstration are categorized and addressed in the following section.

3.5. Rural Communication Needs

This section is composed of comments expressed by the stakeholders of the project on needs for rural first-responder communication.

3.5.1. Voice

The state of Wyoming is in the process of building a statewide interoperable voice network called WyoLink. Based on the level of equipment that most responders currently have at their disposal, the project team determined that discussion of replacing current voice technology with voice-over digital IP-based networks using MANET would not be constructive and might bias stakeholder opinion against the project.

3.5.2. Alpha/Numeric Paging

Fire responders in Hot Springs County currently use pager technology for responding to fire calls. Use of paging is problematic as it is being replaced by cellular service providers. Rural agencies cannot afford the expense of cellular for all responders, many of whom may be volunteers. Paging networks can cover a large area at low cost.

3.5.3. Cellular Communication

Cellular or PCS communication systems are available in Hot Springs County but only near major roadways and towns. Currently Thermopolis has EV-DO cellular service provided by Verizon. Cellular service is expensive for some rural agencies such as volunteer fire departments. And while it may be possible to get a grant or other allotment of funds for the purchase of equipment, money for ongoing costs such as monthly service fees is difficult or impossible to find.

Data communication is not currently used by public safety agencies in Hot Springs County as mobile data terminals (MDTs) are not available. However, many of the stakeholders are very familiar with the technology and had suggestions on its use. A three-county region including

Hot Springs County is currently attempting to get a grant for the purchase of data terminals for its vehicles.

3.5.4. Video

Responders said the ability to send and receive video could be an important tool. Firefighters, for instance, said that video transmission from the scene would be useful at the start of a fire to better coordinate subsequent response. Receiving video from aircraft overhead would also be useful in fighting fires.

3.5.5. Sharing Photos

Stakeholders said that being able to transmit photos taken at the scene of an incident should be a priority for data communications. Although taking photos of incidents is common, the stakeholder group wanted to be able to display a picture to show to responders at a scene. A group of responders could view images of an incident scene by gathering around a data terminal, and using the visuals provided to help plan their response.

It was suggested that this would be useful in the search for missing persons or suspects, and in serving warrants. According to the group, the service of a summons is often done by different agencies working together, and might involve whoever is in the area and responds to a call. If BIA officers are serving a summons, they might get help from a sheriff's deputy from a nearby county, or a game warden in the area. A picture received over a radio network could be shown to officers at the scene of a search for a suspect or missing child. Some group members complained that officers wait "all the time" for photos during a search and often have to go back to the station to get a printout.

3.5.6. Mapping

Responders in Hot Springs County currently have mapping technology available for their use. The sheriff's department vehicles have MDTs with Global Positioning System (GPS) and use commercial software to provide maps and routes.

The stakeholder group also suggested that Automated Vehicle Location (AVL) and maps with property information would be useful. When shown a map with moving icons at the demonstration, the dispatcher for the area asked, "You mean I could see where my guys are?" Also, having property information available to responders would allow them to know who owns a piece of land. They said they now find themselves "scribbling on maps."

Officers in tactical operations expressed that they always need to know "who is there" and "where they are" during incidents. Mapping must be done in real-time, and mapping of residences and schools was especially important.

3.5.7. Email

Roving officers want the ability to send and receive photos and emails. Email is used by departments and by responders at home so it is easy to see the benefit on the job or during an incident. Description of the type of information shared by email on the job was not specified by the stakeholders.

3.5.8. Weather Information

Getting weather information remotely, primarily forecasts and weather alerts, is of great use to all responders. For fire personnel, weather information is a necessity as it can be a matter of life and death. As recently as the summer of 2000, a firefighter lost his life in a weather-related incident when a major wind event caused a fire in Hot Springs County to grow by 16,000 acres.

Stakeholders also suggested that vehicles could be used to record and transmit weather information, particularly during a fire.

3.5.9. Access to Databases

Access to law enforcement databases was discussed in detail by the stakeholders in the first meeting. Many different regional and national databases were discussed as being important to securely access.

3.6. Communications in a Rural Environment

3.6.1. Characteristic Rural Problems

Rural first responders face unique problems when responding to incidents. There are often too few responders from any one agency to handle a situation so responders from different agencies or disciplines may have to assist. Some responders are volunteers and may be employed by multiple agencies at a single incident. For example, of 29 firefighters in the Hot Springs area, five also serve as law enforcement officers.

The size of an incident in rural locations may be large. The terrain can be varied and difficult. Responders may be moved to an area by road, four-wheel-drive vehicle, helicopter, or in some cases must travel on foot.

Often an incident may occur across jurisdictional boundaries, where coordination is necessary and a matter of common practice. In some cases federal and local interoperation is required. During an incident such as a hostage situation on the Wind River Reservation there may be coordination of rural fire and ambulance, the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF), federal marshals, the U.S. Drug Enforcement Administration (DEA), the Federal Bureau of Investigation (FBI) and other federal agencies. Incidents can cross multiple county or federal jurisdiction boundaries.

Responders may be out of radio communication during an incident. Sometimes an officer must travel back to base to exchange information, or dispatch must relay messages between officers on the same force or between officers in different jurisdictions. Frequently relaying messages adds delay and confusion to incident response.

In some situations such as a search, the responders may be spread out and unable to communicate through any method other than radio. And even when they are in off-road, back-country areas with spotty communication coverage, they still want real-time voice and data. Often responders need communication in canyons or shadowed basins where none would be possible even with the best stationary systems.

3.6.2. Personnel Limitations

Rural responders must sometimes wear multiple hats, as there are often too few responders in any one agency to handle an incident. Responders expressed that during an incident they cannot afford "one more thing to do," such as setting up a radio or repeater to provide a communications network.

There is a varying level of interest and technical knowledge among rural responders. Some responders embrace technology enough to carry a GPS unit and a laptop computer while on patrol in the back country where the mode of transport is a horse. Others find technology distracting even in a small city where cellular coverage is possible.

3.6.3. Equipment Limitations

It is important that all vehicles have the same or "interoperable" communication equipment. A network is needed to facilitate communication from the vehicle to the station. Officers cannot do license and registration checks at every traffic stop due to the poor coverage of the communications network.

3.6.4. Funding Limitations

The Hot Springs County Sheriff's Department actively seeks money for equipment upgrades and purchase. This project is an example of its ability to get funding. Rural agencies often must be creative and use a variety of sources. The most common types of funding opportunities are for the purchase of equipment. However, funding for the upkeep and maintenance of equipment is difficult to get from common sources, and often impossible to get from local sources.

4. SCENARIOS

4.1. Introduction

Rural and small public safety and law enforcement agencies face many of the same challenges as their large urban and suburban counterparts in providing responsive and effective public safety services. These tasks require effective coordination, command, control, communication, and sharing of information with numerous criminal justice, public safety agencies and public utilities [3, 58]. However, in contrast to urban locales, rural areas often face additional difficulties and complexity from the lack of communications infrastructure, large distances and rugged terrain.

This project began with a request from the Hot Springs County, Wyoming, Sheriff's Office for "assistance in addressing and overcoming communications challenges they face in day-to-day operations." The challenges of rugged terrain, lack of infrastructure, low population, large area, severe weather, and limited resources are faced generally by public safety agencies in remote, rural areas. Hot Springs County, however, demonstrates extreme variations of these challenges and provides a demanding environment in which to test possible communications solutions. Specifically, this project identified MANET as a potential means of addressing these pressing needs.

Gaining a comprehensive understanding of the needs of rural public safety operations formed the foundation for this project. An overall goal was to develop a standardized routing protocol for MANET that met the applicable requirements of the Department of Homeland Security's Statement of Requirements for Public Safety Wireless Communications & Interoperability (SoR). In particular, the protocol must address the challenges of implementation in remote rural locations such as Hot Springs County.

In order to achieve these goals, the first project objective was to work in partnership with the Hot Springs County stakeholder group to identify and define realistic operating situations, both actual and potential. In parallel with the SoR, these incidents provided the benchmarks against which the appropriate routing protocol could be developed and allowed protocol evaluation under relevant testing. They also served as a direct means of identifying and describing the needs and challenges faced in public safety operations conducted in rural areas.

To facilitate development and adequate protocol testing, realistic scenarios of a large enough size (number of communication nodes) had to be developed, simulated and analyzed. This section describes a representative cross-section of realistic situations and associated communications challenges faced by rural public safety agencies. It also focuses on the methodology behind scenario development, including how and what information was collected, what obstacles were encountered, and lessons learned.

4.2. Methodology

Information surrounding incidents that occur in urban areas, especially communication documentation, appears more readily available in literature, including the SoR, than for incidents that occur in rural areas. Such resources are sparse in rural locales unless an individual is actually on-site and collecting documentation in real time. In rural areas, such an expert resource would most likely be directly involved in the incident.

As the project progressed, it became apparent to the researchers that documenting the real, known facts of an incident and choosing breadth over depth would be the most valuable to the project and the Hot Springs County public safety officers. A direct consequence is that it was deemed difficult if not impossible within this scope of work to derive incident detail equivalent to that presented in the SoR. However, the research team, with the help of Hot Springs County responders, could identify particular aspects of these incidents where mesh networking technology could be of most benefit. In turn, assumptions could be simplified and the facts developed into scenarios with the necessary level and type of detail needed for the OPNET modeling system and protocol evaluation. Ultimately, the protocol testing was conducted using scenarios based on realistic situations where mesh networking technology made sense for effective incident response (see Figure 2).

Document, collect, and organize facts about incidents.

→

Identify situations where applying mesh networking technology could be beneficial.

→

Collaborate to develop scenarios with the necessary type of detail to enter into the OpNet modeling system (i.e., locations, trajectories).

↓

Evaluate protocols under relevant conditions using the scenarios

Figure 2: Scenario Documentation Overview.

While different situations required slightly different technical information, in general, the scenario development process was straightforward. Potential incidents for further review were identified and a basic outline was developed. Facts surrounding the incident were gathered, including who was involved, what kind of equipment was used, and what emergency action plans were employed. These facts were distilled into a rational narrative that incorporated a sequence of events and a potential list of communication nodes.

Because most of the identified incidents did occur or would occur over the course of many hours, days, or even weeks, the research team chose a period of time during the incident for which testing the mesh networking technology would be valuable to stakeholders. For example, an earthquake, dam breach, and subsequent flooding would be an incident of massive proportions that responders and emergency relief workers may be working on for weeks after the precipitating event. In this scenario, with input from Hot Springs County stakeholders, the research team chose to focus on the period of time involving the initial evacuation of Thermopolis. The mesh networking technology may be very beneficial in coordinating a quick and effective evacuation. The steps taken to document incidents follow:

Identify Incidents

The research team worked with stakeholders to identify potential incidents or representative incidents that had already occurred.

- Black Mountain fire—actual incident occurred October 18, 2004
- Earthquake, breach of Boysen Dam—potential incident
- Hazardous materials spill in Wind River Canyon—potential incident; modeled after train derailment and chlorine spill near Alberton, Montana, that occurred August 11, 1996
- River search: potential incident; based on narrative of similar situation
- Kate's Basin fire—actual incident occurred August 5–18, 2000

Incident Outline

The research team worked with Hot Springs County public safety officials to develop an incident outline describing essentially what happened and the real or anticipated response. The incidents were separated into particular segments of time according to incident operations. Specific instances were acknowledged for MANET protocol testing.

Gathered Facts

As appropriate, the research team attempted to gather the following information:

- Incident maps, GIS information, key locations (e.g., incident command posts or headquarters, road blocks, actual spill dimensions, toxic cloud movement, fire progression, detours)
- Participants: List of departments, agencies, groups, or individuals involved in the incident and how they were (or would be) involved
- Number and type of personnel from each of the above entities
    - What kind of equipment they use(d), including communications equipment
    - What their tasks were or would be
    - Where and how they moved or would move throughout the incident
    - Command structure
- Detailed timeline/sequence of events
    - Incident Action Plans (IAP)
    - Communication logs
    - Shift tickets
- Evacuation and detour execution, maps, and plans
- Emergency Action Plans
- Photographs and/or video of the incident

Incident information was gathered through in-person or telephone interviews of public safety officers, modeling of similar incidents, emergency action plans, and a review of the relevant literature. The research team tapped the following sources for information and facts surrounding the identified incidents:

- Hot Springs County Sheriff's Office
- Hot Springs County Fire Department
- Hot Springs County Emergency Management
- Bureau of Reclamation

- Bureau of Indian Affairs, Wind River Agency
- Frenchtown Rural Fire District
- Montana Rail Link
- Pacific Northwest Team 3 National Incident Management Team
- Numerous print and online sources addressing specific incidents and types of incidents

4.3. Scenarios

The following sections depict a number of real and potential incidents identified by the researchers and the Hot Springs County Sherriff's Office as being illustrative of the challenges faced by rural incident responders. The descriptions include physical locations, participants, and a sequence of events/narrative. The amount of detail and method of presentation vary according to the information available concerning the incident. All of the scenarios were established from the perspective of Hot Springs County public safety. Scenarios that are more regional in nature, such as the flooding from a breach in Boysen Dam, would necessarily affect more than the City of Thermopolis. For the purposes of this project, however, incident areas and participants were defined according to the parameters of Hot Springs County.

4.3.1. Black Mountain Fire

This scenario represents a real event that occurred October 18, 2004. It is based on a detailed narrative given by a Hot Springs County law enforcement officer who was directly involved in the incident. It is further discussed in the section entitled Rural Public Safety Needs Assessment.

The Black Mountain Fire is a powerful example of the challenges faced by rural incident responders, particularly rugged terrain and long distances. Placing an officer in harm's way in order to relay critical radio traffic across a rough environment is a difficult decision. The mesh networking technology that is the focus of this project could reduce and even eliminate the need for such a decision.

4.3.1.1. Location

Black Mountain is a four-mile-long ridgeline that rises up to 1,100 feet over the surrounding terrain in eastern Hot Springs County (HSC). The incident area is defined by the grass fire that occurred at the southwest end of the mountain and traveled over the ridge to the northeast. The area's infrastructure consists of several oil wells, pipelines, oil storage units and buildings containing chemicals. All equipment had to travel on paved and dirt roads approximately 30 miles northeast of the town of Thermopolis (see Figure 3). Traversing the mountain to fight the fire was made easier by the oilfield roads leading to the wells scattered on all sides of the mountain.

The majority of the fire was under control within two hours of the initial response, although mop up continued for several more hours. The fire burned approximately 20 acres before it was controlled and out. No oilfield assets were lost or damaged. Figure 4 shows the area burned by the fire.

Figure 3: Route from Thermopolis to Black Mountain fire site.

Figure 4: Responder locations and area burned by the Black Mountain fire.

4.3.1.2. Participants

The first personnel to arrive at the scene of the fire were two deputies from the Hot Springs County Sheriff's Department. Shortly afterward, four trucks from the Hot Springs County Fire Department arrived with the fire chief. Three hours into the incident, fire vehicles from the Bureau of Land Management (BLM) arrived. Since the fire occurred on BLM land, when BLM personnel arrived on the scene they took control of the incident (see Table 2).

Table 2: Participants in the Black Mountain fire incident.

Agency	Units
Hot Springs County Dispatch	HSC Dispatch
Hot Springs County Sheriff's Department	HSC Sheriff 1, 2
Hot Springs County Fire Department	HSC Fire 1, 2, 3
	HSC Fire Tanker
	HSC Fire Chief
	HSC Fireman (radio courier)
Bureau of Land Management	BLM Fire Personnel

4.3.1.3. Sequence of Events/Narrative

This section briefly describes the events surrounding HSC's response to the Black Mountain fire and adds information about communications that would have been helpful in responding and controlling this fire.

<u>Sequence of Events</u>

1. Fire reported to HSC public safety answering point (PSAP) by oil field worker.
2. Location identified. Fire is on BLM land.
3. Dispatch is identified and responders notified.
    a. Sheriff's officers
    b. HSC fire department
    c. BLM fire response
4. Responders progress to fire site.
    a. Sheriff's officers first on scene.
    b. Determine if additional responders will be necessary.
5. Power outage in the oil field. East side of Black Mountain is on fire and black smoke is in the trees.
6. Local fire department responders second on scene.
    a. Establish Initial Incident Command.
    b. The fire trucks, IC and tanker truck deploy to fight the fire.
    c. Establish common RF connectivity among responders.*
    d. Assign responder responsibilities.
    e. Start to suppress fire.
    f. Notify BLM of common channel frequencies.*
    g. BLM fire crew can monitor fire activities as it approaches.*
    h. Power company is contacted.
7. BLM fire crew remote from fire site; third on scene—establish Final Incident Command.
8. Continue to suppress fire.
9. The fire is suppressed and the deputies leave, followed by the fire trucks.

* This will be performed automatically when the Statewide WYOLink P25 trunked radio system is in place.

The following is an actual radio log completed by the dispatcher working the Black Mountain fire:

Event	Time
Dispatch manned	1719
Deputies en-route 2 units	1720
Engine 9 en-route 2 men	1720
Engine 13 en-route 2 men	1724
Fire Chief En-route	1724
Engine 6 en-route 2 men	1725
Engine 10 en-route 2 men	1727
Power out in oil field	1727
East side of Mountain on fire and in trees black smoke	
Engine 14 at fire hall	1732
BLM Notified by dispatch	1732
Deputies Arrive	1745
Engine 9 arrived	1756
Engine 13 arrived	1814
Engine 6 arrived	1827
Engine 14 en-route 2 men	1830
Engine 7 arrived	1841
Radio problems on mountain need more portables	
Sheriff's Deputy moves to ridge to relay traffic	1845
Fireman responding with radios	1937
Contacted Power Company	1957
BLM has Command of fire	2010
Radio carrier returns to fire hall	2057
BLM calls off the fire department	*2230*
Engine 13 en-route to town	2236
Engine 9 en-route to town	2238
Engine 13 and 9 out for fuel	2321
Engine 13 and 9 at Fire Hall	2329

4.3.1.4. Challenges and Further Information

Of the five incidents discussed here, the Black Mountain fire had the most complete and accessible information in regards to sequence of events, personnel, equipment, movement, and communications. The dispatcher's radio log provided an additional perspective.

The information for this incident was more readily available for a couple of reasons. First, this was an actual incident that occurred in Hot Springs County and not, as in some of the other scenarios, speculation on a situation that has not occurred. Hot Springs County provided the initial response and a large portion of the fire control activities before BLM personnel arrived and assumed command. The fire was relatively short in duration, and a local, current public safety officer was directly involved in the response and thus able to provide a significant amount of detail.

The records concerning BLM participation would have enhanced the situation analysis, but were not available. The duration of the communications between individuals on the scene and particularly the type of information being requested or communicated would also have been helpful in documenting and developing this scenario. Photographs or video, both aerial and terrestrial, in addition to maps and GIS information would have improved the overall scenario representation.

4.3.2. Earthquake/Boysen Dam Breach/City of Thermopolis Evacuation

This section describes an imaginary earthquake, sudden breaching of Boysen Dam on the Wind River, and subsequent flooding and evacuation of the town of Thermopolis and surrounding areas. An evacuation conducted under pressure of time provided a different type of incident in which to test the routing protocols.

It should be emphasized that this scenario has not occurred. However, it was developed using the Emergency Action Plans for Hot Springs County and Boysen Dam, in addition to the expertise and experience of incident responders and managers.

4.3.2.1. Location

The upper reaches of the Big Horn River are commonly called the Wind River and the two rivers are often termed the Wind/Big Horn River. The Wind River begins along the north slopes of the Wind River Mountain Range in west central Wyoming. It flows southeastward to Riverton where it meets the Little Wind River. From there, the Wind River flows northward through the Wind River Canyon and the Owl Creek Mountains. On the north side of the canyon and just south of Thermopolis at an area called the Wedding of the Waters, the Wind River officially becomes the Big Horn River.

On the northern edge of Fremont County, just before the Wind River enters the Wind River Canyon, the river is dammed to form Boysen Reservoir (Figure 5). The zoned earthfill dam was completed in 1952 by the Bureau of Reclamation and has a structural height of 220 feet. The reservoir has “a total controlled storage capacity of 802,000 acre-feet at a water surface elevation of 4725 feet” [4]. The three-part Boysen Unit of the Pick-Sloan Missouri Basin Program includes a power plant in addition to the dam and reservoir. Power generation, irrigation, flood control, sediment retention, fish propagation, and recreation development are all benefits of the regulated streamflows provided by the dam.

Figure 5: Boysen Dam looking north to the Wind River Canyon.

The city of Thermopolis, with a current population of approximately 3,200 people [5], is the county seat of Hot Springs County. The city is situated on the banks of the Wind/Big Horn River and is home to the world's largest mineral hot spring.

For the purposes of documenting this scenario, the incident area was defined as follows:

- The area in the immediate vicinity of the dam, power plant, and operations building, including Boysen State Park.
- The predicted inundation area of a flood caused by the breach of the dam, including the Wind/Big Horn riverbed north from the dam to the towns of Thermopolis and Kirby, the Wind River Canyon, and the area between the mouth of the canyon and Thermopolis that will be affected by the flood waters. See Figure 6 and Figure 7.
- The evacuation route from Thermopolis, northwest along Highway 120 to Meeteetse and Cody.

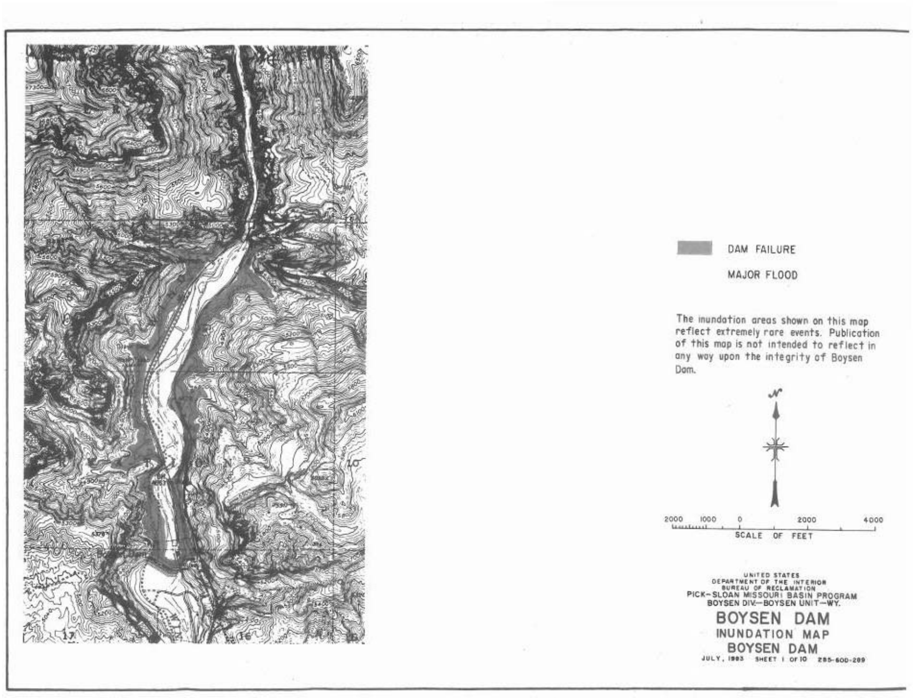

Figure 6: Inundation area from Boysen Dam north through the Wind River Canyon [6].

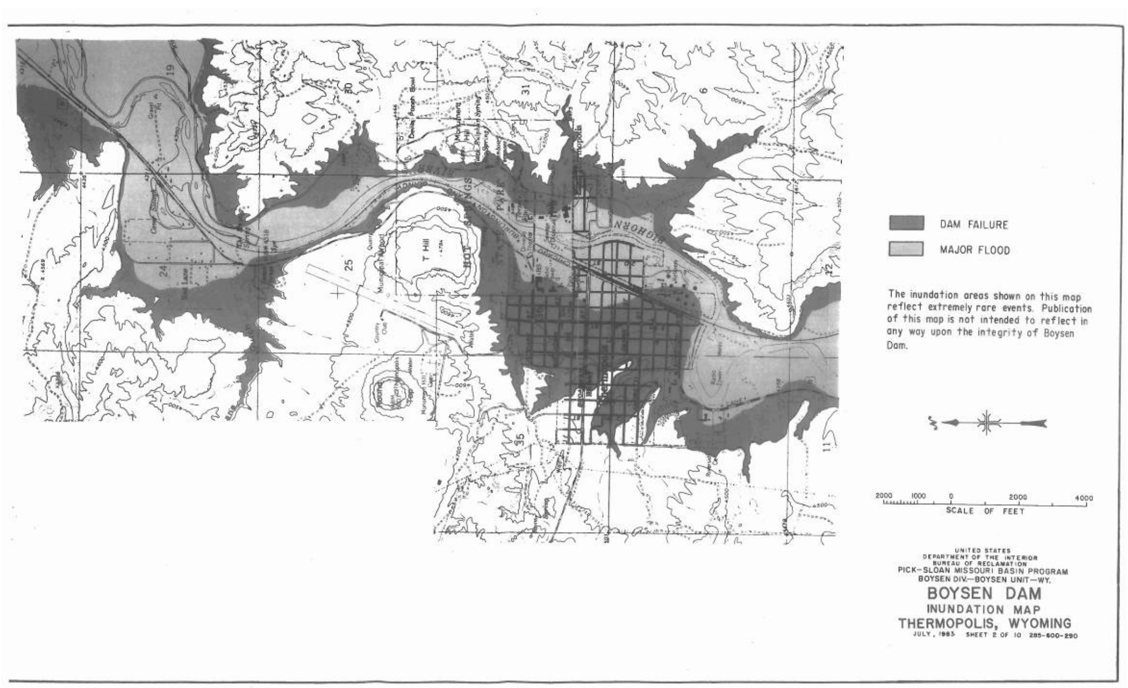

Figure 7: Inundation area surrounding Thermopolis and northward [6].

4.3.2.2. Participants

If this incident were to occur, it is anticipated that the following participants would be involved:

- Bureau of Reclamation: Boysen Dam office, Wyoming Area Office (WYAO), and Casper Control Center (CCC)
    - At the dam itself if it was staffed. Staffing is only one shift four days per week (M-R, 7:00 am to 5:30 pm). Boysen Dam Operating Personnel includes the Facility Manager, Big Horn Field Branch and Powerplant Supervisor.
    - Public information personnel from the Great Plains Regional Office.
- Wyoming Highway Patrol
- Fremont County law enforcement and emergency services (ambulance, fire, search and rescue); Shoshoni Police Department
- Incident Command Post in Thermopolis (Emergency Operations Center)
    - Incident commander
    - Information officer
    - Dispatch
    - Department of Transportation
    - Bureau of Reclamation
- City of Thermopolis Police Department—three vehicles, one person per vehicle
- Hot Springs County law enforcement/Sheriff's Office—three vehicles, one person per vehicle
- Hot Springs County Emergency Medical Services—three ambulances, three people per ambulance
- Hot Springs County Search & Rescue—three vehicles, one ATV, one boat
- Hot Springs County Fire Department—possibly Hazmat team in addition to fire fighting duties and/or emergency medical response
- Western Area Power Administration (WAPA)
- National Weather Service
- Local radio station
- Evacuee transportation (bus drivers)
- Neighboring counties (Washakie/Big Horn—river flow; Park--evacuees)
- Hospitals and medical facilities in neighboring counties along evacuation route
- Railroad
- Airplane doing aerial surveillance of damage
- Water treatment facilities; power, gas, pipeline operators
- Wyoming Geologic Survey; National Earthquake Information Center USGS in Golden, CO
- Boysen State Park—one ranger
- Wyoming Office of Homeland Security
- U.S. Army Corps of Engineers

4.3.2.3. Sequence of Events/Narrative

The time the breach occurred would determine some emergency actions. For example, if this happened at night schools and businesses would be closed and more people would be in their homes. The disabled, elderly and other populations might use the buses for evacuation, and the evacuation orders would need to be delivered more directly to individual homes. Also, an earthquake may damage the dam, but the damage may not be manifested as a breach until weeks later. In this instance, more warning will be possible.

From the county line (Fremont and Hot Springs) at mile marker 117 it would take about 11 minutes to get out of the canyon (not necessarily to higher ground). From the dam, it would take about 17 minutes.

1. Earthquake hits and dam breach begins to occur. It will take approximately two hours for the flood waters to reach Thermopolis.
2. Bureau of Reclamation would call Wyoming Highway Patrol, who would then notify downstream authorities. WYAO or CCC would warn Fremont and Hot Springs Counties' sheriff and EMS (Dispatch Center) or the dam operator would make the notification to the counties. Regular updates would be provided.
    a. If the dam is staffed at the time of the breach, dam personnel would notify the area office in Mills (Casper), Wyoming. They would go down the call out list and notify agencies according to the Call Down Chart. During non-staffed hours, the CCC would be responsible for notifying the WYAO, Boysen Dam operating personnel, downstream authorities, and WAPA.
3. Emergency sirens activated (one south of town, one in town, and one in Kirby (north of Thermopolis)).
4. Radio station (KTHE 1240 AM) and Riverton National Weather Service office alerted to broadcast emergency message.
5. Command and command post established.
    a. Sheriff or Emergency Management Coordinator would be Incident Commander.
    b. Command post would be located at the fire department because it is the only emergency/law enforcement service on high ground/outside flood plain.
    c. Information officer gathers information and presents it to incident command personnel including the Wyoming Department of Transportation and the Bureau of Reclamation.
6. Emergency Operations Center/Dispatch (portable) established wherever the Incident Commander (IC) is stationed. The Middle School is the designated meeting place for emergency events. Fanout calls made. (Fanout means all emergency services are activated and placed throughout Hot Springs County in order to deal with other calls as needed.)
    a. Fire Department personnel would be staged at their building. All vehicles would be on standby and ready for use. The river rescue vehicle and watercraft would be used for stranded persons.
    b. Law Enforcement, Sheriff's Office—depending on the situation, off-duty personnel may be called in to assist.
    c. Law Enforcement, City Police Department
    d. Search and Rescue, Fire Department, and Ambulance placed on standby in vehicles in a safe place (i.e., high ground).
        i. Ambulance—one northeast of town, one northwest of town, one in town
        ii. Search and Rescue
7. Evacuation ordered by IC.
    a. Law enforcement would be responsible for coordinating evacuation procedures. As an example, the Hot Springs County Undersheriff would go to the south end of

the city, use his public address system and announce the warning to get people out of the potential inundation area.
    b. Personnel with communication devices out ahead on highway to provide information for evacuees.
    c. Dispatch would call:
        i. Bus barn—during the school year, the buses will be used for school children; during the summer, buses would be used for individuals with special needs.
        ii. Hot Springs Memorial Hospital
        iii. Schools—Hot Springs County High School, Lucerne Intermediate, Ralph Witters Elementary, Thermopolis Middle School
        iv. Assisted living facility—Thermopolis Rehabilitation & Care Center
        v. Big Horn Enterprises, Inc. (for people with disabilities).
8. Dispatch pages Fire Department, Ambulance, and Search and Rescue and advises them to move all equipment to high ground at the Middle School.
9. Dispatch notifies neighboring counties (landline telephone):
    a. Fremont County Sheriff's office
        i. No more traffic through the canyon. May already have been alerted by the Bureau of Reclamation. Highway 20 must be closed.
    b. Washakie County Sheriff's Office
        i. Close Highway 20 to all traffic.
    c. Big Horn County Sheriff's Office.
    d. Park County Sheriff's Office.
        i. Prepare for evacuation traffic and evacuees.
        ii. Evacuation route is along Highway 120. Close road to southeast-bound traffic.
10. Wyoming Highway Patrol notified
    a. Close road to traffic into Hot Springs County on Highways 20 and 120.
11. Gates would close Highway 20 south into Wind River Canyon. Initially, one person (law enforcement) would be stationed there until risk became too great (i.e., flood waters too close).
12. Roadblocks would be set up. A person and a vehicle would be stationed at each.
    a. Roadblock no. 1 would be placed close to the Washakie/Hot Springs County line along Highway 20 and as far from Thermopolis as possible.
    b. Roadblock no. 2 would be placed close to the edge of Thermopolis along Highway 120 to facilitate people coming out but not going in.
13. Wyoming Office of Homeland Security notified.
14. If a terrorist act is suspected, the FBI must be notified.
15. Pipeline operators notified.
16. Residents in homes that will be unaffected will be told to stock up on fresh water supplies.
17. Town water treatment plant notified.
18. Hot Springs County might attempt to alert people in the canyon with their car radio (truckers), but they would not be going into the canyon.

4.3.2.4. Challenges and Further Information

This scenario was challenging to research, document and develop simply because it has not occurred. Wide-scale flooding on the Wind River/Big Horn River has occurred in the past but is not common. Earthquakes rock parts of Wyoming on occasion, but are rare. Dam breaches are also uncommon. However, the 1976 breach of the earth-filled Teton Dam in Idaho and the resulting flood provided insight into the scale and magnitude of such an incident and the necessary level of response required [7, 8, 9]. The Wyoming Multi-Hazard Mitigation Plan [10] developed by the Wyoming Office of Homeland Security also offered data on the frequency and magnitude of floods and dam failures in Wyoming, and provided possible mitigation strategies. Other literature sources provided background information on the crucial nature of early warning systems and procedures. This information was important for establishing the impact of such an incident and illustrated a solid potential application for mesh networking technology. Preparations for wide-scale evacuation of Thermopolis were also made during the Kate's Basin fire discussed below and would be the first response in a large flood situation. For these reasons, documentation efforts focused on first alerts and immediate evacuation.

Because this is a potential incident concern, the Emergency Action Plans for Hot Springs County and Boysen Dam, along with the interview of a Hot Springs County law enforcement officer, proved to be the most valuable in developing a potential scenario. These three sources outlined a practical and appropriate, step-by-step response to such a disaster. The Bureau of Reclamation also provided inundation area maps, which were especially useful in discussing evacuation procedures.

4.3.3. Hazardous Materials Spill

This scenario describes a train derailment and subsequent spill of hazardous materials (chlorine) deep in the Wind River Canyon. Again, it should be emphasized that this particular incident has not occurred. However, trains regularly carry hazardous materials on the route through the canyon (Figure 8) and accidents involving cargo do occur along the highway. This incident was modeled after an actual incident that occurred near Alberton, Montana. The Alberton area is remarkably similar to the Wind River Canyon with the railroad tracks, a river, and a highway running through a narrow canyon, in addition to the proximity of residential areas and a town. As with the previous scenario, the Emergency Action Plans for Hot Springs County, the 2008 Emergency Response Guidebook [11] for hazardous materials, and the expertise and experience of incident responders and managers were all used as guidelines to develop this potential scenario.

Figure 8: Train hauling hazardous materials through the Wind River Canyon.

Particularly for this type of incident, the number and type of agency personnel and communications will vary depending on what time frame is considered, whether immediately after the incident, or during evacuation, command and action plan establishment, or clean-up and mitigation.

This scenario illustrates a situation where data communication, such as human vital statistics, would be particularly important. In addition, limited connectivity because of rugged terrain and remote location, multi-agency jurisdiction and involvement, evacuation or “shelter-in-place” orders, traffic-control limitations and lengthy detours to coordinate are just a few of the challenges this type of incident would present. Both the highway and the railroad are prime north–south routes. Quickly re-opening them to safe travel would be critically important. Mitigating the spill as quickly as possible would, of course, be crucial from an environmental standpoint as well.

The following section describes the actual hazardous materials incident that occurred near Alberton, Montana. The potential hazardous materials incident in the Wind River Canyon was modeled after the Alberton incident and is described second.

4.3.3.1. Alberton, Montana, train derailment and chlorine spill

This incident occurred over twelve years ago, and most official documentation has been archived. A couple key articles and websites were located after an intensive search. The Frenchtown fire chief who acted as the incident commander initially expressed keen interest in the project and offered assistance to the research team in accessing records, reports, and news coverage of the incident. Montana Rail Link, the rail carrier operating the train that derailed, was also contacted.

On April 11, 1996, around 4:00 a.m., 19 cars from a Montana Rail Link train derailed near the town of Alberton, located about 34 miles northwest of Missoula. According to the 2000 U. S. Census, Alberton has a population of about 375 people. “Six of the derailed cars contained hazardous materials. One derailed tank car containing chlorine (a poison gas) ruptured, releasing 130,000 pounds of chlorine into the atmosphere; another tank car containing potassium hydroxide solution (potassium cresylate, a corrosive liquid) lost 17,000 gallons of product; and a covered hopper car containing sodium chlorate (an oxidizer) spilled 85 dry gallons onto the ground [12].” About 1,000 people from the surrounding area were evacuated. Interstate 90 (I-90) is about 150 yards north of the railroad tracks where the accident occurred. The toxic chlorine cloud drifted across I-90 and caused a number of traffic accidents, chlorine related injuries, and stranded motorists. The interstate was closed for 19 days and a lengthy 200-mile detour was required [13]. Damage was estimated at $3.9 million [12], although the total cost was estimated to be several hundred million dollars [13]. “The economic effects to the area were felt for many years afterwards, including road repair from detoured traffic, pine trees browned or killed by the chlorine gas cloud, rendering them susceptible to forest fires, and lawsuits due to injuries” [13].

4.3.3.2. Description (Alberton incident)

<u>Incident Area Layout</u>

The train derailment and subsequent chlorine spill occurred in the narrow Clark Fork Canyon, about two miles west of Alberton (Figure 9). The railroad tracks lie on the south side of the river, while I-90 runs parallel on the other side of the river. The town of Alberton lies along the Interstate and the river just inside the Mineral County border with Missoula County. The area is forested, mountain foothills, through which the Clark Fork Canyon runs. See Figure 10 and Figure 11 for approximate locations.

Figure 9: Alberton train derailment and chlorine spill [13, 14].

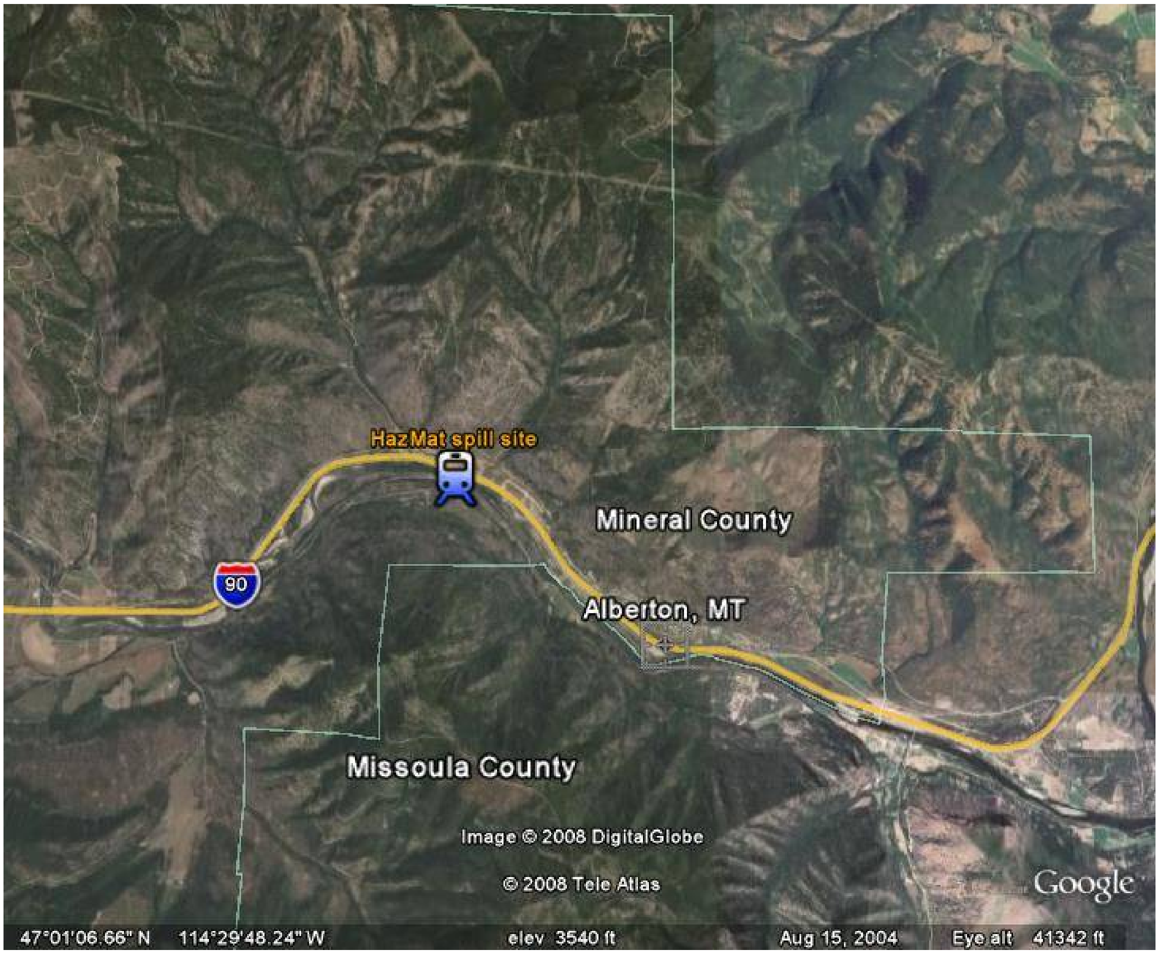

Figure 10: Approximate location of train derailment and spill site.

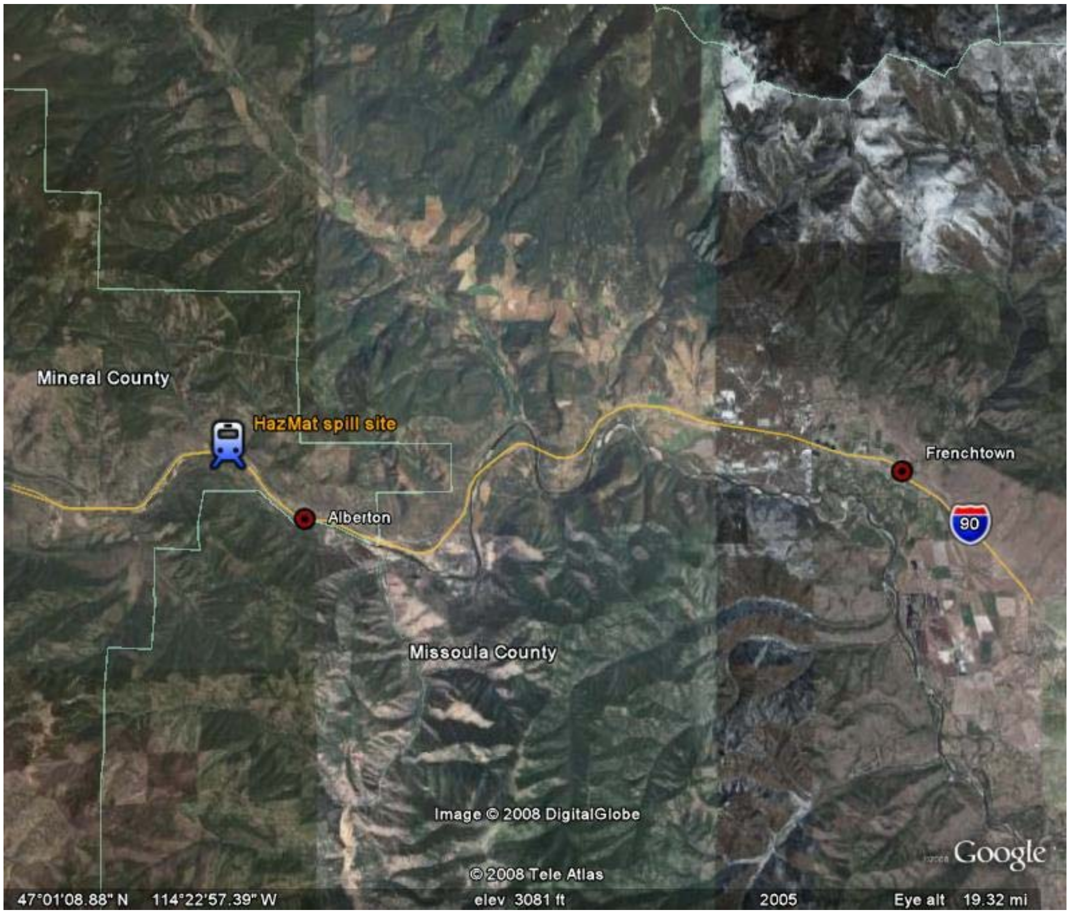

Figure 11: HazMat spill site in relationship to Alberton and Frenchtown, and Missoula and Mineral Counties.

Immediately after the derailment, the chlorine gas cloud spread rapidly eastward from the incident site across I-90 and into the town of Alberton. An unofficial report based on vegetation being completely wiped out indicated the spill site was approximately 300 feet by 50 feet. "Ambient chlorine level monitoring at the accident site was reported to be between 12 and 52 ppm" [13]. According to the Centers for Disease Control and Prevention (CDC) the level at which chlorine is "Immediately Dangerous to Life and Health" is 10 parts per million (ppm) [15]. Though the incident site itself was timbered and the area sparsely populated, approximately 1,000 people were evacuated from the town and surrounding area. The evacuation area was roughly a four-mile radius around the spill site. The resulting detour for local and I-90 travelers was initially 81 miles, but had to be extended to about 200 miles because the roads could not handle the traffic. Some larger vehicles were unable to use that detour. The evacuation orders and detour were in place for 19 days while the spill was cleaned up [13].

Participants

Initially, no one in the area surrounding the accident site was aware that a potentially toxic spill had occurred. The derailment occurred a little after 4:00 am and by daybreak the local emergency response personnel had been notified by the railroad that chlorine had been spilled. The Alberton fire department had no Hazmat training or personal protection equipment to deal with chlorine. However, Frenchtown, a small community about 15 miles east of Alberton and in neighboring Missoula County, has a pulp mill in which chlorine is used and the local fire department was trained and equipped for dealing with chlorine releases. The Frenchtown fire chief became the incident commander. The governor declared a state of emergency for Mineral and Missoula counties [12, 13].

Approximately 20 government agencies, the railroad, the general public, and various private entities were involved in the spill aftermath. After people were evacuated and the detours were set up, the Frenchtown fire department created a HazMat task force to take care of livestock and other animals left behind. Montana Rail Link and EPA personnel were primarily responsible for the cleanup and stabilization of the site [13].

Eleven years after the Alberton incident, the Frenchtown fire chief who acted as the incident commander was the keynote speaker at the Regional Fire Prevention and Hazardous Material conference held in Casper, Wyoming. His experiences in dealing with over 20 agencies and other entities to manage the evacuation and clean-up of the spill were the focus of the presentation. The rural area where the incident occurred caused some unique challenges for response and clean-up. These challenges were presented along with several recommendations for others managing hazardous materials incidents.

Some of these challenges mentioned were [13]:

- The "transportation bottleneck" caused by the 19-day closure of I-90. Roadblock management was a significant issue and the derailment divided the region in half [16].
- Alberton is in Mineral County right on the line between Mineral County and Missoula County. Communications between the counties was limited [16].
- Rural people had to be located and evacuated.
- Livestock and other animals were left behind and had to be fed and watered.
- Legal issues with working on railroad property dictated that responsibility for the cleanup rested primarily with the Environmental Protection Agency and railroad personnel. The Frenchtown fire department was not directly involved in clean-up efforts even though the fire chief was the on-scene commander.
- "The State of Montana Department of Environmental Quality was not prepared to take over responsibility after the spill [13]."
- The task of coordinating numerous entities—some 20 governmental agencies, the railroad, the public, various private groups or individuals—was daunting.
- Each governmental agency had its own protocol, making coordination difficult.
- Holding public meetings was also difficult because attorneys were present and encouraging people to sue.
- Aggressive corrosion of clean-up equipment, including vehicles, tires, and air compressors, added adversity to the already challenging clean-up procedures.

The fire chief and incident commander made some further observations and recommendations [13]:

- "Evacuation: Who plans it, who does it, where do the people go, and how are the people maintained? A responsible party who pays the bills and feeds them is necessary.
- Evacuation vs. shelter in place. Shelter in place is an option only when evacuation is not possible. There are liability risks if you don't offer evacuation as an option. If persons refuse to go, adults might be allowed to stay, but children can be removed.

- There are legal issues involved in working on private property. The responsible party has a say as to whether the hazard is no longer present.
- Let federal agencies such as the EPA do their job and make the tough decisions.
- Documentation is absolutely necessary. This includes conversations with the Principal Responsible Party and with the many agencies. Who is responsible for billing and collection?
- Expect the unexpected. Each situation is different, and there will be many governmental agencies and private groups to deal with, including such diverse agencies as the Coast Guard and the FBI, and a government funded group from University of Michigan Business School gathering data on how area businesses are affected.
- When does the Incident Command terminate? Who makes the decision? Get policies, SOPs.
- Long term financial costs hard to recover especially without adequate documentation.
- Make a project termination list (toxic chemicals removed, contaminated soils removed, etc.).
- Don't cozy up to the Principal Responsible Party or other group.
- Maintain public trust. Videos and public meetings go a long way.
- Expect to be called to testify in court. Get experts. Attorneys look for 'deep pockets.'"

These lists provide practical concerns for public safety personnel and bring to light not only the challenges to incident response in rural areas, but also a number of opportunities where mesh networking would enhance communications and thus incident response. The importance of adequate documentation of incidents is a key point especially applicable to this project.

4.3.3.3. Location (Hot Springs County incident)

The Wind River carves the narrow and steep Wind River Canyon in central Wyoming. The canyon begins at Boysen State Park in Fremont County, just below the dam that forms Boysen Reservoir. The canyon and river wind north for approximately 19 miles before opening abruptly and approaching the town of Thermopolis. Busy Highway 20 and an active rail line follow the river closely and on opposite sides through the canyon. A number of homes are scattered throughout and the area is popular for recreational pursuits, including fishing and white water rafting. The canyon falls entirely within the borders of the Wind River Indian Reservation. Any incident that occurs within the canyon must be addressed by more than one jurisdiction.

The incident area is defined by the area immediately surrounding the derailed train and toxic spill, the zones established for mitigation and clean-up, and the response path of the two HazMat teams that initially respond to the spill. It is further defined by the locations and movements of law enforcement officers conducting traffic control and the direction of travel for the toxic cloud. If this situation were to occur, the incident area would also include areas to be evacuated or ordered to "shelter in place," and potential evacuation routes.

4.3.3.4. Participants (Hot Springs County incident)

Ziplines, boats, helicopters, and vehicles coming down the railroad tracks would all be used to access the derailed train and the spill site. If a hazardous materials spill of this nature occurred, the following participants would be communicating with each other to manage the incident:

- Driver who calls in the derailment

- City of Thermopolis Police—two vehicles, one person per vehicle
- Hot Springs County Fire Department HazMat team—one truck, three people per truck
- Hot Springs County Volunteer Fire Department—three trucks, each with two people
- Riverton Fire Department and HazMat team
- Three to five people on the Regional HazMat team from Worland would assume command after arriving at the site
- Ambulance/EMS—two ambulances, each with up to three people, depending on the number of injuries; Life Flight helicopter
- County Law Enforcement—two vehicles, one person per vehicle
- Wyoming Highway Patrol—possibly three vehicles
- City of Greybull
- Department of Environmental Quality
- Environmental Protection Agency
- Weather personnel—Hot Springs County Fire Department; City of Riverton
- Wyoming Department of Transportation
- Burlington Northern Santa Fe Railroad
- Bureau of Indian Affairs, Wind River Indian Reservation
- Crowd control personnel
- Hospitals—Thermopolis, Riverton
- Water Department personnel
- Game & Fish, Livestock Board, U.S. Fish & Wildlife Service, animal shelter
- Wyoming Office of Homeland Security
- Search & Rescue
- TV/Radio stations
- (National Transportation Safety Board)
- (Federal Railroad Administration)

The location of the spill in the canyon will primarily determine the level of evacuation that may be required. Weather elements, such as wind direction and precipitation, will also be determining factors in immediate incident response and subsequent mitigation. Conducting an evacuation of the City of Thermopolis would be similar to operations for the flooding scenario described above. However, Highway 20 would be an additional route. Evacuations to the south would also need to be considered.

4.3.3.5. Sequence of Events/Narrative (Hot Springs County incident)

1. Train derailment occurs. Individual traveling in the canyon makes the call to 911. There is no cell phone or landline telephone coverage in the canyon so it would take at least 15 minutes from the time the incident is noticed for the call to come in. Lack of telephone coverage is also why the railroad would not be able to report the incident.
2. Dispatch notifies:
   a. City of Thermopolis Police Department
   b. Hot Springs County and Fremont County Fire Departments (HazMat teams)
   c. Ambulance and Emergency Medical Services
   d. Hot Springs County Sheriff's Office

   e. Wyoming Highway Patrol
   f. Burlington Northern Santa Fe Railroad
   g. Also involved and notified as appropriate
      i. City of Greybull
      ii. Department of Environmental Quality (State)
      iii. Environmental Protection Agency (Federal)
      iv. Weather personnel—Hot Springs County Fire Department; City of Riverton
      v. Wyoming Department of Transportation
3. Incident Command System (ICS) established.
   a. Command Post set up.
   b. Safety Officer assigned.
   c. Material identified.
   d. Incident Action Plan developed.
   e. Weather elements noted (e.g., wind direction and speed).
4. Fire department HazMat teams act as incident command leaders and the only responders within the hot and warm zones.
   a. HOT ZONE: Area immediately around the incident where contamination exists. All personnel working in the Hot Zone must operate in teams of two.
   b. WARM ZONE: Zone where decontamination activities take place.
   c. COLD ZONE: Clean area outside the contamination control line where command and support functions take place. Special protective clothing is not required in this area.
5. Wyoming Highway Patrol closes the north entrance to the canyon with the gate. One person and vehicle remain stationed there. The south entrance is closed with a barricade. One person and vehicle also remain stationed there.
6. EMS/ambulances are stationed outside the canyon.
7. Emergency sirens activated (one south of town, one in town, and one in Kirby (north of Thermopolis)).
8. Radio station (KTHE 1240 AM) and Riverton National Weather Service office alerted to broadcast emergency message.
9. If warranted, fanout calls are made and Emergency Operations Center is set-up. Emergency Operations Center/Dispatch (portable) established wherever the Incident Commander (IC) is stationed. The Middle School is the original designated meeting place for emergency events. (Fanout means all emergency services are activated and placed throughout Hot Springs County in order to deal with other calls as needed.)
10. Questions to consider:
   a. Perimeter set up? *All personnel operating in or around the perimeter must be logged in and out.*
   b. Traffic control?
   c. Crowd Control? (i.e., Onlookers must be kept upwind.)
      i. Search and Rescue
      ii. Resources from neighboring counties?
         1. Washakie County Sheriff's Office
         2. Fremont County Sheriff's Office
         3. Big Horn County Sheriff's Office

4. Park County Sheriff's Office
   d. Injuries? Mass casualties?
      i. Ambulances requested?
      ii. Hospital put on alert?
      iii. Life Flight needed?
      iv. Victims or responders needing decontamination?
   e. Evacuation necessary? *(See Scenario 2. Evacuation routes could include Highway 20 north to Worland.)*
   f. Terrorist ct suspected? If yes, notify the FBI.
11. Call CHEMTREC. CHEMTREC is a "public service hotline for fire fighters, law enforcement, and other emergency responders to obtain information and assistance for emergency incidents involving chemicals and hazardous materials [17]."
12. Notify Wyoming Office of Homeland Security.
13. Establish a public information site.
14. Obtain weather forecast information.
15. Immediate next steps:
    a. Determine need for heavy earthmoving equipment.
    b. Obtain food and water for responders.
    c. Monitor responders wearing chemical protective clothing for heat-related health problems.
    d. Determine involvement and/or threat to Wind/Big Horn River.
    e. Determine threat to Thermopolis drinking water intake.
    f. Locate storm sewers.
    g. Contact Hot Springs County Public Health Department and Officer.
    h. Contact Wyoming Game & Fish Department, U.S. Fish and Wildlife Service, and Wyoming Livestock Board.

4.3.3.6. Challenges and Further Information

While this scenario had a relatively sound model to emulate, documentation again proved challenging. The incident in Alberton occurred over 12 years ago and all of the records had been archived. Additionally, while the spill happened near Alberton, the Frenchtown Rural Fire Department responded because it had the nearest HazMat Response Team. Frenchtown is located in Missoula County while Alberton is in Mineral County. Incident records are housed in the Missoula County courthouse in Missoula and were not readily available for this study. Also, Montana Rail Link was unresponsive to requests for information.

Because this incident did not occur in the Wind River Canyon, development of the scenario depended primarily on the Emergency Action Plans for Hot Springs County and interviews with Hot Springs County law enforcement. Technical information concerning the handling of chlorine and other hazardous materials proved useful in establishing the parameters of dealing with a toxic spill.

An interview with a member of Hot Springs County's HazMat team could have provided more details on who would be involved in this type of spill and how responders might move and communicate during the initial response and throughout mitigation. Additionally, a HazMat team member might have been able to describe in detail an incident in which he or she participated that occurred in Hot Springs County or the surrounding area. Other important information that would be helpful for developing this type of scenario might include detour maps, incident action plans and zone boundaries, photographs, video, weather data and impacts on the evacuation and mitigation strategies, and more information on the volume and type of communication necessary in the initial response and subsequent evacuation coordination and mitigation for a hazardous materials spill of this nature.

4.3.4. River Search

The stakeholders in this project identified a number of more common scenarios where enhanced data communication would be beneficial. A missing person search along one of Wyoming's rivers was one of those situations. From a protocol testing perspective, this scenario is simpler than those discussed previously. However, it does present some unique challenges to rural incident responders. A situation of this type would require responders to move along a meandering line in a set pattern. To ensure a thorough search, responders need to maintain a set spacing from each other and from the river, in addition to moving at a regulated pace. Limited sight because of riparian growth and uneven terrain could impede such movement. Easy access points may also be limited because of terrain or land ownership. Responders could be on foot, riding all-terrain vehicles (ATVs), in boats or driving automobiles.

This scenario was designed solely for the purpose of simulation and protocol testing. However, the idea and outline of events was based on a narrative described by a BIA stakeholder.

4.3.4.1. Location

The incident area is defined by an approximately 16-mile stretch of the Wind River in Wyoming. The search area followed the river and stretched approximately 100 yards in both directions from the river's banks (see Figure 12).

Figure 12: Orientation of river search scenario.

4.3.4.2. Participants

Participants in a river search scenario of this type would include county search and rescue volunteers, law enforcement officers, emergency medical personnel and an ambulance, trained search dogs and their handlers, and community volunteers. Depending on the duration and magnitude of the search, resources and volunteers from neighboring jurisdictions may be called in.

4.3.4.3. Sequence of Events/Narrative

A fisherman is reported missing after spending the day fishing in the vicinity of a bridge over the Wind River. The search begins downstream along the north and south river banks. Searchers on foot and on ATVs parallel the river at equal intervals from each other. The ATVs drive ahead and the individuals on foot follow behind calling the person's name. Search and rescue personnel in vehicles drive along roads from river access to river access to fill in coverage and communicate with searchers on foot and riding ATVs. See Figure 13 for a representation of how the responders moved during this incident. The search process ends when the fisherman is found and deemed safe.

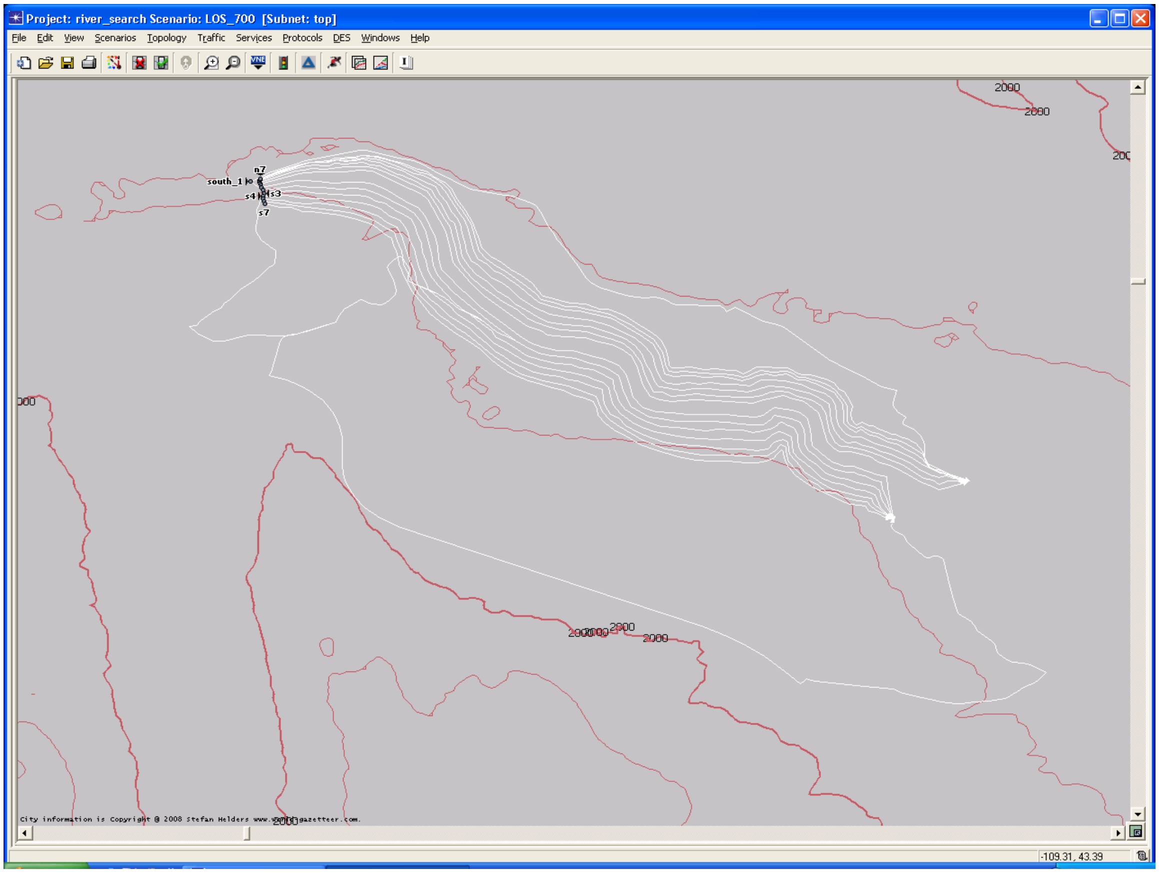

Figure 13: Trajectories for individual responders conducting the river search.

4.3.4.4. Challenges and Further Information

As mentioned above, this scenario was created for protocol evaluation purposes only. However, several different search and rescue situations were discussed as possible scenarios for this research project. Search and rescue incidents are relatively common for public safety personnel in Hot Springs County and surrounding areas. Many times these incidents are in rugged or remote terrain with little infrastructure.

To enhance this scenario for documentation purposes, the following information would be useful:

- Detailed list of who would be involved and what kind of equipment they would be using
- Description of how different individuals or vehicles would move in relation to the terrain, the type of search, and other search groups or individuals
- Sequence of events
- More accurate and detailed description of communications, including frequency and volume of communication, who communicates with whom and how, and what type of communication takes place
- Interview of search and rescue personnel in Hot Springs County who have participated in such an incident operation

4.3.5. Kate's Basin Fire

This section describes a large wildfire that burned in August of 2000 primarily on the Wind River Indian Reservation southwest of Thermopolis in Hot Springs County. After the initial attack, the fire was contained in only 12 days, but it consumed approximately 137,600 acres during that time. Damages were estimated at over $2.5 million, including the destruction of large amounts of prime grazing land and a tribal timber sale [18].

This wildland fire incident was identified early in the project as a compelling example of the challenges faced by rural incident responders. The fire's location required several jurisdictions to initially respond, followed by statewide resources, and eventually national incident management teams and firefighters from around the United States. The terrain is rough with steep, rocky slopes. The area is also remote with little infrastructure or roads. Spread these two factors over a large area and effective communications for incident management becomes even more difficult. An investigative report specifically cited terrain and inadequate communications infrastructure as significant and problematic factors in fighting the Kate's Basin fire. Many firefighters were unfamiliar with the area and environmental conditions were especially volatile over the course of the fire [19]. All of these factors combined highlighted the need for reliable data communication of current conditions and situations.

4.3.5.1. Location

The incident area is defined by the fire, which burned 137,600 acres over the course of two weeks and claimed the life of one Arkansas firefighter. The Kate's Basin fire complex started as two separate lightning-ignited fire incidents on the Wind River Indian Reservation. In less than a week, the Blondie No. 2 and Kate's Basin fires were being managed as one complex and national incident management teams were being assigned to the fire [18]. Refer to Figure 14 for a map of the fire's progression.

The northeastern edge of the fire burned within eight miles of the town of Thermopolis. In numerous locations, fire burned down the western walls of the Wind River Canyon (Figure 15). The western part of the fire area (Blondie No. 2) consisted of heavy timber. Grass and low sagebrush were fuel for the eastern part where the Kate's Basin fire originated. The topography is generally mountainous running east–west along the Owl Creek Mountain range. The area where the fatality occurred ranges in elevation from 5,000 to 6,646 feet, with slopes of 20 to 25 percent [19].

The command center for the fire was initially set up in Riverton, about 40 miles southeast of where the lightning strike started the Kate's Basin fire. Eight days after the fires were reported, the command center was moved to Thermopolis.

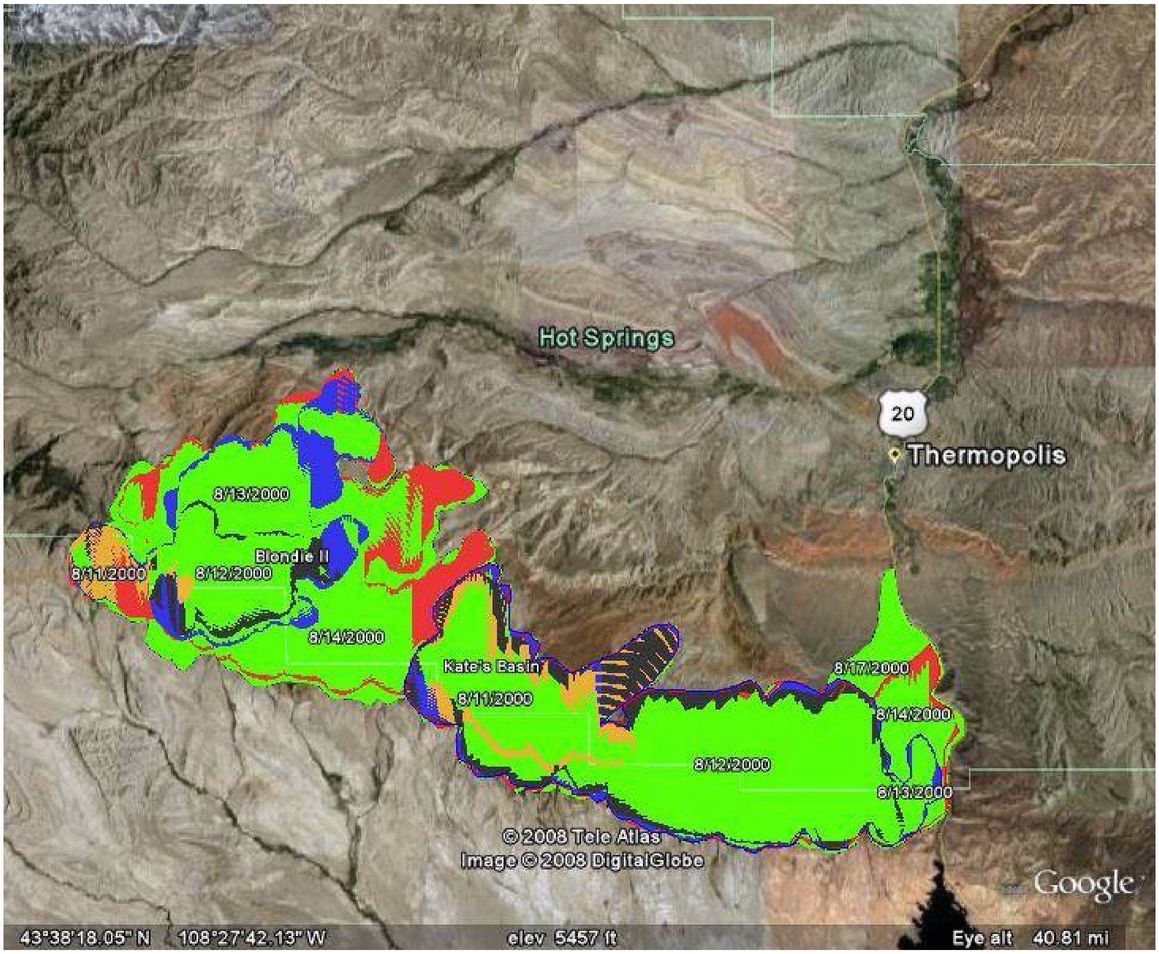

Figure 14: Kate's Basin Complex fire progression.

Figure 15: Kate's Basin Complex fire burning in the Wind River Canyon [20].

4.3.5.2. Participants

The fire was originally reported to the Wind River Agency in Fort Washakie. Initial attack began immediately under the direction of the agency forester and fire management officer. An Incident Commander Type 4 conducted fire operations. Type 2 and Type 1 National Incident Management teams were assigned over the course of the fire. Fort Washakie Dispatch made numerous requests for resources working through the Cody Dispatch Center and the Rocky Mountain Coordination Center.

At the peak of operations, 751 firefighters were involved in fighting the blaze [21]. Engines, pumper trucks, bulldozers, water tenders, helicopters and air tankers helped crews gain control of the fire. The charts in Figure 16 detail the equipment and personnel that provided support during the course of the fire.

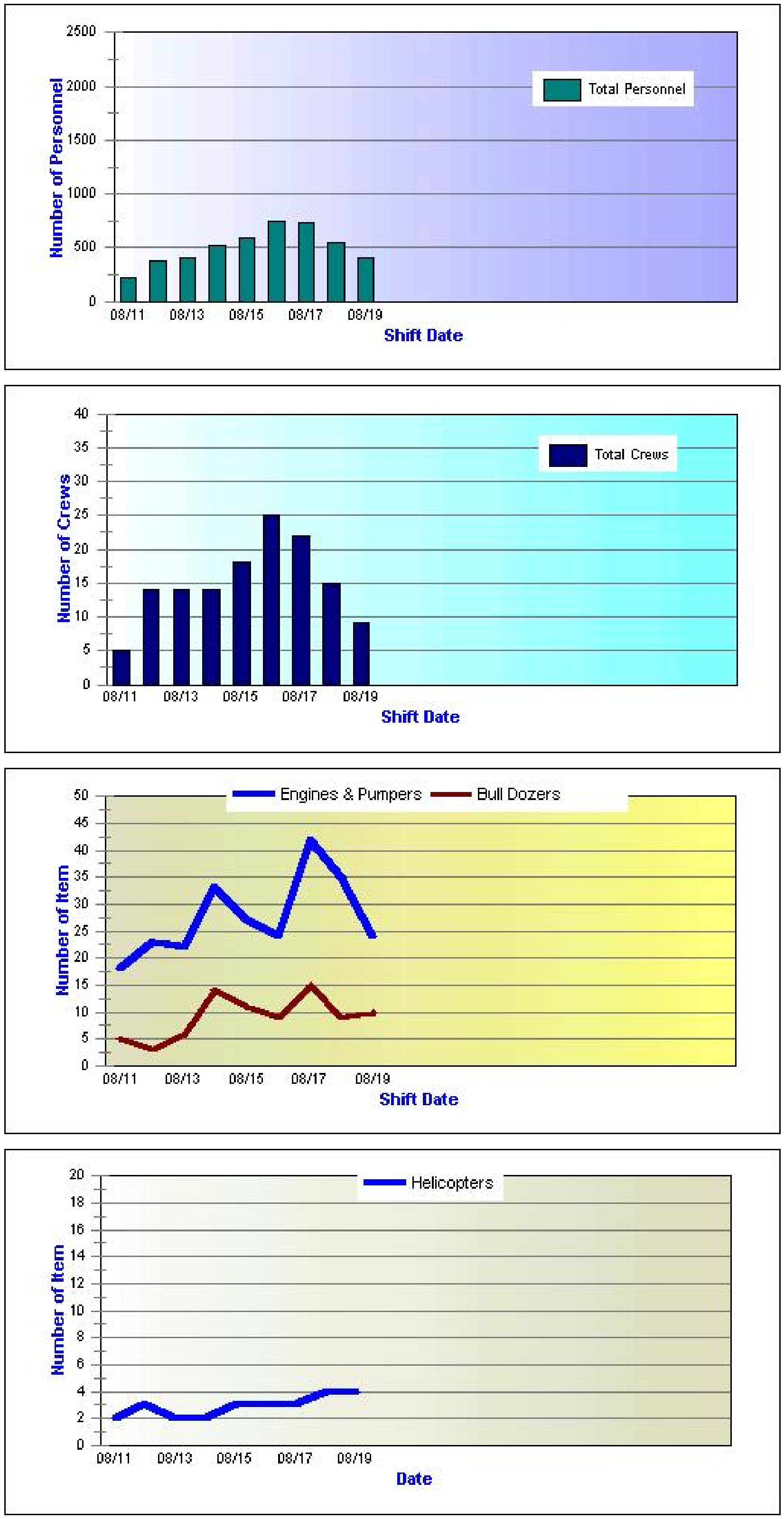

Figure 16: Personnel and equipment historical charts for the Kate's Basin Complex fire [21].

The following agencies, organizations, and individuals participated in fighting the Kate's Basin Fire Complex:

- NorCal No. 2 Incident Management Team
- Type 1 Incident Management teams
- Type 4 Incident Management teams
- Bureau of Indian Affairs
- Arapaho Tribe
- Shoshone Tribe
- National Weather Service
- U.S. Forest Service
- BLM
- National Park Service
- Fremont County
- Hot Springs County
- State of Wyoming
- Private citizens, companies
- Fort Washakie Dispatch
- Cody Dispatch Center
- Rocky Mountain Coordination Center

4.3.5.3. Sequence of Events/Narrative

The following table summarizes a brief sequence of events surrounding the wildfires that came to be known as the Kate's Basin Complex (Table 3). This information was compiled from the daily Incident Management Reports of the National Interagency Coordination Center (NICC) [18], and the Kate's Basin Fatality Report [19]. The NICC is part of the Center for International Disaster Information. Both groups provide resources and central coordination points for large-scale incident response.

Table 3: Sequence of events for the Kate's Basin Complex wildfire.

Date (year 2000)	Time	Size in acres (KB/BL)	% Contained (KB/BL)	Estimated Containment (KB/BL)	Event
5-Aug					Lightning ignites two fires on Wind River Indian Reservation in Wyoming.
7-Aug	14:00				Fires reported to Fort Washakie Dispatch Center, Wind River Agency.
7-Aug	14:00				Initial attack begun immediately.
9-Aug	5:30	15,000/1500	0/10	15-Aug/13-Aug	18 miles SW of Thermopolis, tripled in size in 5 hours. Blondie crossed containment lines.
10-Aug	5:30	17,000/1700	20/60	15-Aug/13-Aug	Type II Incident Management Team requested (competition tight). KB torching in timber and making runs. BL fire within 1/4 mile of ranch and large commercial timber sale. BL burnout planned for Aug 11.
11-Aug	5:30	33,000/2500	20/60	15-Aug/14-Aug	KB grew 16,000 acres. BL and KB will now be managed as one complex. Burnover of engine resulted in one fatality and one injury.
12-Aug	7:00	33,000/4,000	20/50	15-Aug/14-Aug	KB major runs pushed by high winds. BL burned timber sale area. Management as a complex starts today.
13-Aug	7:00	77,419	1	unknown	Strong runs driven by high winds and hot temps. Thermopolis, ranches at risk.
14-Aug	5:30	83,000	10	unknown	Very active (high winds, high temps., low relative humidities). BL spreading.
15-Aug	5:30	87,000	10	unknown	Command post will move from Riverton to Thermopolis today. Fires very active.
16-Aug	5:30	127,600	50	unknown	West flank and NE corner burned out to control lines. Fire made runs in the interior. Control problems include steep rugged terrain, cliffs, limited access, extremely dry fuels.
17-Aug	5:30	128,600	70	18-Aug	Spike camp established.
18-Aug	5:30	128,600	85	18-Aug	Burnouts on SW flank.
19-Aug	7:00	137,600	100		2.5 million dollars C-T-D?
KB=Kate's Basin BL=Blondie #2					

A detailed investigation was conducted of the circumstances surrounding the fatality that occurred during this fire. The following table summarizes the sequence of events leading up to and after the fatality (Table 4).

Table 4: Sequence of events surrounding the fatality that occurred during the Kate's Basin wildfire as described in the investigative report [19].

Date	Time	Event
30-Jul		One strike team of four (4) Type 6 engines had been ordered on July 30th for the Middle Enos fire. (Chickasaw Nation #2, Oklahoma (OK) Egnines #2, #4, #10).
10-Aug		Strike team released from Worland Dist. BLM, Middle Enos Fire.
10-Aug		Chickasaw Nation #2 assigned to Kate's Basin Fire. Oklahoma engines assigned on severity to BLM-Worland, who loaned Oklahoma Engine #2 and #10 to Kate's Basin fire w/ understanding that they would return to Worland if needed for initial attack.
10-Aug	15:00	Oklahoma Engines #2, #10 reported to Kate's Basin Fire. Assigned suppression duties North of Mexican Pass.
10-Aug	22:30	OK #2, #10 bedded down beside engines at "Dip Tank" camp.
11-Aug	5:00	Shift starts.
11-Aug	8:30	Briefing by incident commander. (Weather forecast transmitted to Incident Commander Brown at 06:30 discussed.) OK #2, #10 assigned suppression duties in the same area as yesterday.
11-Aug	12:30	OK #2, #10 directed to Mexican Pass to help hold the line. Unfamiliar w/ area. Went to West side and worked on active fire.
11-Aug		OK #2 directed by radio to Mexican Pass.
11-Aug	20-30 min. after previous	OK #10 finished filling water tank and proceeded to Mexican Pass.
11-Aug		OK #2 meets up with Hot Springs County (HSC) Egnine #7 and a Hot Springs County "quick attack" engine. OK #2 foreman and HSC #7 foreman discuss tactics. No other supervisor on site.
11-Aug	14:15	Grass Creek Divide RAWS (23 miles NW of entrapment site) reported: winds at 37 mph, 86 degrees F, 11% relative humidity.
11-Aug		OK #2 leaves HSC #7 and scouts two-track and dozer line to the East.
11-Aug		OK #2 turns around at intersection of two-track road and dozer line. Now heading West.
11-Aug		Winds up to 40-45 mph, flame lengths 25-30 ft; cause OK #2 to retreat in reverse to the East up the two-track. Become entrapped.
11-Aug		After backing 60 ft., OK #2 Foreman leaves truck cab to wet down immediate area. Pump quits after 4-5 sec.
11-Aug		Further retreat to the East in reverse. Engine stalls.

Table 4: Sequence of events surrounding the fatality that occurred during the Kate's Basin wildfire as described in the investigative report [19].

11-Aug		Foreman separates from vehicle and heads East up the two-track. Driver deploys fire shelter inside the engine cab after being unable to exit because of winds.
11-Aug		HSC #7 recognizes trouble, heads East with hoses deployed.
11-Aug		HSC #7 suppress fire and puts injured OK #2 driver into their engine.
11-Aug		HSC #7 extinguish fire on their own engine.
11-Aug		OK #2 driver uses handheld radio to contact OK #2 Foreman.
11-Aug		HSC #7 moves west away from fire.
11-Aug		OK #2 Foreman retreats up two-track for approx. 900 ft. Leaves the road to the south.
11-Aug		OK #2 Foreman loses hard hat 30 ft from the road.
11-Aug	14:30	OK #2 Foreman overcome and fatally injured by the fire approximately 230 feet south of the two-track. Clutching hand-held radio and partially deployed fire shelter.
11-Aug		OK #10 arrives, wet-lining to the north. Hears radio traffic of incident. Proceeds back to the two-track and around OK #2, toward ridge top. Doesn't locate Burnett.
11-Aug	14:50	Fort Washakie Dispatch, Don Mitchell, Bob Jacob, Superintendent Perry Baker notified of incident.
11-Aug	14:54	Two helicopters (43T, 53F) dispatched. Locate OK #2 foreman and secure the site.
11-Aug	15:31	Helicopter 43T transports OK #2 driver to Riverton Hospital.
11-Aug		Agency personnel immediately begin serious accident notification process. Agency law enforcement investigate, HSC Coroner responds and removes the body.
11-Aug	As accident occurring	NorCal #2 Type II Incident Management Team arrives to take over the fire. Assist OK firefighters from engines #4 and #10.
12-Aug	6:00	Fire transferred to above team.
12-Aug	13:00	OK #2 Driver released from hospital.
12-Aug	14:00	Delegation of authority to conduct the accident investigation.

An Incident Action Plan (IAP) contains strategies for the overall management of the incident in addition to specific steps to be taken during an operational period. IAPs were developed for each operational period during the fire and maps were associated with each. Figure 17 provides an example.

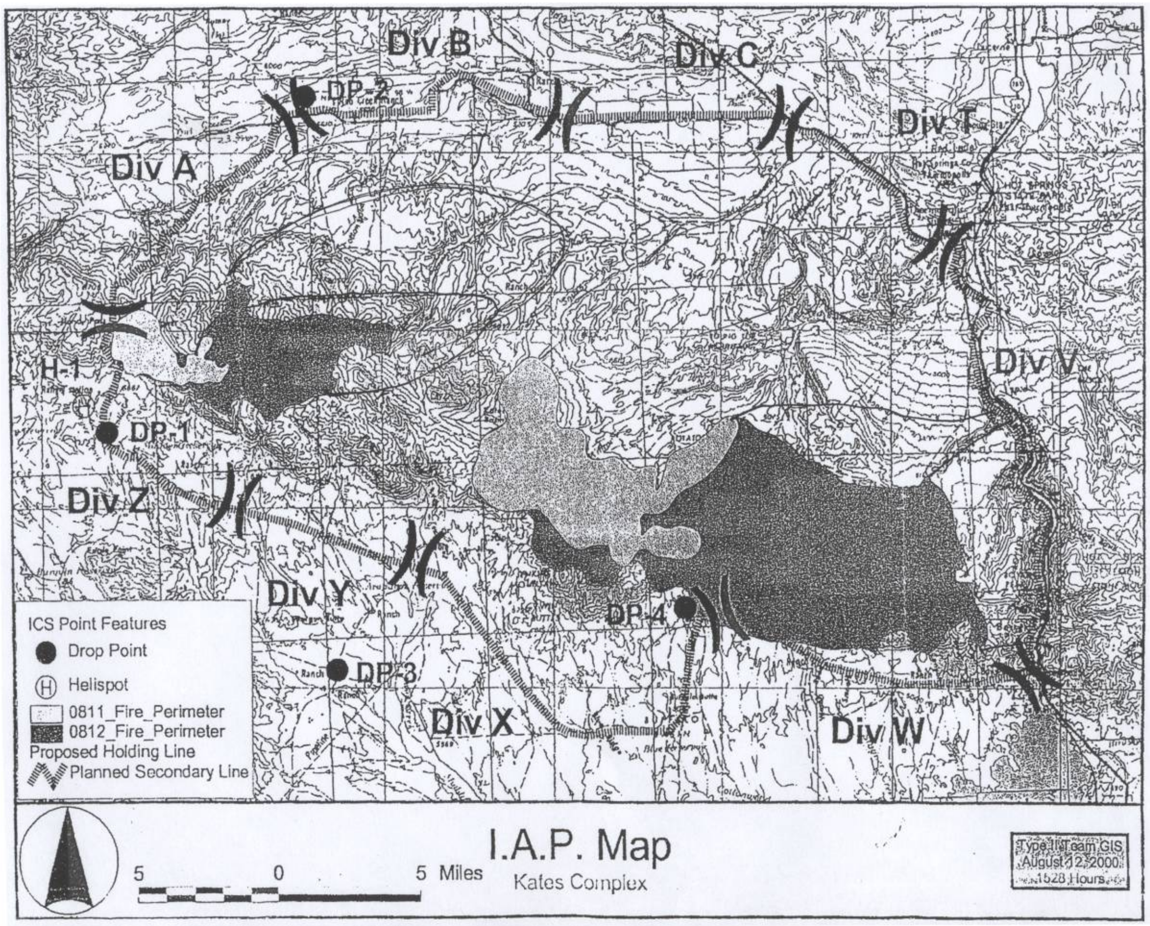

Figure 17: August 12, 2000, Incident Action Plan map for Kate's Basin Fire Complex [22].

4.3.5.4. Challenges and Further Information

Obtaining official documentation for this fire was difficult. Information was unavailable or simply did not exist. A website published by the National Incident Management team assigned to the fire provided the most detailed and useful information. The individual responsible for fire management at the Wind River Agency was able to present information as well. An unexpected contact during the demonstration for this project led to a scrapbook of pictures and newspaper articles documenting the entire fire and its effects on the region.

The following information was sought in order to adequately document this complex incident for the purposes of this study, but success in obtaining the information was limited:

- Incident Action Plans for each operational period
- Daily incident maps
- Final fire narrative or more detailed sequence of events
- Lists of personnel and equipment

- Generalized movement and allocation of resources
- Photographs documenting the incident

The Kate's Basin fire was a large and complex incident. The research team identified two time periods that would serve as a scenario with which to evaluate the protocols. As mentioned previously, an in-depth review of the events and conditions surrounding the fatality was conducted. Information concerning locations, movements, and communication was available. Because of the sensitive nature of the unfortunate occurrence, a scenario could have been developed using the report documentation but omitting any mention of a fatality. The second time frame involved the burnout up the mouth of the Wind River Canyon just south of Thermopolis (Figure 18). Several stakeholders were familiar with this part of the firefighting operation and provided some insight into what activities were conducted. Due to time constraints, however, the research team was unable to gather the minimum amount of information that would be required to properly evaluate protocols using this scenario.

Figure 18: Burnout along and up the west side of the mouth of the Wind River Canyon, just south of Thermopolis [23].

4.4. Conclusions (and next steps)

The research team used a simple interview and research process to document and develop scenarios that would be of interest to rural public safety officers in addition to being valuable for protocol evaluation according to the requirements of the SoR. Representative incidents were identified and outlined, facts were gathered, and a narrative was produced that included general movements and possible communication nodes. Different sources were used to flesh out the outlines and develop workable scenarios.

The experience of the research team in documenting these incidents illustrates the lack of resources available for rural public safety operations and, perhaps, the discrepancy that exists between urban and rural jurisdictions. In some instances, the best source of information was the memory of a responder. In other cases, the data was archived or did not exist. In many cases, when asked for information, personnel did not have the time or resources to assist, even though they expressed interest in supporting the project and were curious about the results.

These issues raise the question of what particular information should be documented for purposes similar to those of this research. While it is necessary to have detailed information for the purposes of communication simulation and protocol evaluation, that information will be unavailable or unrealistic if the scenarios and situations in general are misunderstood or undocumented.

4.5. Recommendations

Based on the results of this part of the project, the research team makes the following recommendations for similar scenario development efforts:

- In general, personal interviews or discussions with public safety officers provided valuable insight into how an incident progressed or might have evolved. In some cases, this may be the only direct source of information concerning an incident. Any project of similar nature or intent would benefit from gathering input from these stakeholders.
- Public safety personnel may not have the resources or time to gather this type of documentation, if it even exists. While the research team was able to collect information through telephone interviews and from print sources available online, conducting this type of research on site may have yielded more information. For example, by traveling to Missoula to review the archived documentation about the Alberton chlorine spill, or visiting the Wind River Agency to discuss the Kate's Basin fire, the research team may have been able to collect the necessary information, and at the same time build useful relationships with public safety officers.
- Real-world experiences of the personnel involved in these types of incidents are important and relevant. Even though written documentation was helpful in some instances, it never revealed the whole picture. If records of the exact events are not available or accessible, an anticipated response or experience from a similar activity can help to accurately fill in the blanks.
- Using the rural public safety needs assessment as a guide, stakeholders should be asked to review these scenarios and define their situational needs. Some important questions to put to stakeholders might include:
  - During these incidents, when would it have been beneficial to share a photograph with another responder or the dispatcher?
  - When would automated vehicle locations be important?
  - Would communication of a victim's vital signs to an ambulance en route or the receiving hospital make a difference?
  - What maps or structural diagrams would be of use?
  - What real-time information would assist you in managing the incident?

5. RADIO FREQUENCIES, DIGITAL BANDWIDTH AND TRANSMISSION RANGE

Radio communication is fundamental to the technology presented in this research. An understanding of this equipment and its strengths and limitations, particularly in rural areas such as Hot Springs County, is fundamental to evaluating the potential of the technology, as is understanding how these components fit into the framework outlined by the SoR.

5.1. System of Systems Model

Current forward thinking in the field of public safety communication involves groups of communication systems covering differing sized areas, as demonstrated by the System of Systems diagram from the SoR—see Figure 19.

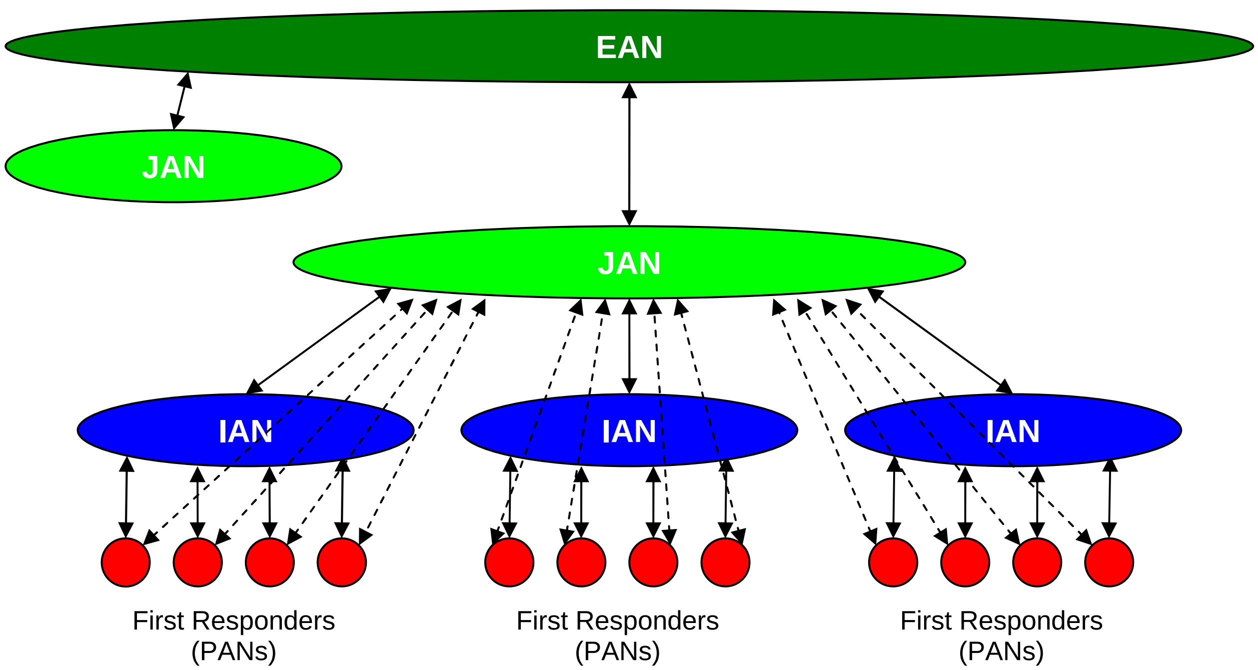

Figure 19: System of Systems.

5.1.1. Extended Area Network

The Extended Area Network (EAN) is a communications network covering a very large area and connecting separate Jurisdictional Area Networks (JANs).

For the purpose of the scenarios studied it is assumed that the EAN is a fixed, wired or fiber network or the Internet. It is assumed that the network is Internet Protocol (IP) based.

5.1.2. Jurisdictional Area Network

A JAN is a wide-area network that is of primary use to public safety first responders. The JAN covers an entire area of operations. For the purpose of this project the JAN covers Hot Springs County and Wind River Canyon.

Frequency bands in the 700MHz spectrum would be ideal for this use in terms of coverage and possible data rate. Propagation coverage for the fixed network will be calculated using 700MHz parameters.

It is assumed that the network is IP based.

5.1.3. Incident Area Network

An Incident Area Network (IAN) is a mobile or nomadic temporary network created at the site of an incident by accumulation of vehicles or by the installation of temporary radio networks.

In this scenario it is assumed that the network performs like an 802.11a or 802.16e network in the licensed 4.9GHz frequency band. It is assumed that the network is IP based.

5.1.4. Personal Area Network

A Personal Area Network (PAN) would be a small network created around a first responder to interconnect devices carried on his or her person. Examples of devices applicable to this project would be handheld computers, wireless earpieces and personal sensors. Communications in a PAN can be achieved by any close-area radio network such as Bluetooth, Zigbee or Ultra Wide Band (UWB).

For the purpose of this project it is assumed that all PAN traffic is transferred to a PDA or like device that communicates with the IAN. PAN traffic will not be modeled.

5.2. Public Safety Communications Equipment

No specific device is assumed in these scenarios. It is assumed, however, that first responders would have the following equipment:

- Handheld VHF high band WYOLink P25 radio
- Handheld voice/data radio device
- Laptop computer
- In-vehicle router
- Video camera
- Digital still camera
- 700 MHz IP based broadband data radio
- 4.9 GHz IP based broadband data radio

The VHF radio is included for completeness, but is not considered applicable to the analysis conducted within this project.

The voice radio, otherwise referred to as a Public Safety Communication Device (PSCD), is a small handheld radio device. The device is capable of receiving a page or text message. For this scenario the voice traffic from the device will be modeled as a Voice Over Internet Protocol (VOIP) or Radio Over Internet Protocol (ROIP) application. The PSCD will be assumed to be dual band and operate on 700 MHz and 4.9 GHz. The output power of the device will be limited as it is a small portable device. The PSCD has an in-vehicle docking station that provides a connection to the vehicle access point.

The laptop computer is capable of accessing a web browser, sending and receiving email and pictures, and controlling the video camera. The laptop has an in-vehicle docking station that provides a connection to the vehicle router.

The in-vehicle router provides a network interconnection of the laptop and PSCD (when docked) and the video camera to the JAN and the IAN radio devices. The interconnection traffic will not be modeled.

The video camera is assumed to be IP based and connected to the in-vehicle network by a GigE wired link. It will be capable of streaming H.263 video. The traffic to the access point will not be modeled.

The digital camera is for taking still images. The camera will be connected to the laptop with a cable, a PAN or a wireless 802.11 network. The traffic to the laptop will not be modeled.

The 700 MHz data radio will be assumed to be a full-power mobile radio device operating in the licensed public safety portion of the 700 MHz band. Specifications for equipment will be derived from commercial 700 or 900 MHz products.

The 4.9 GHz data radio is assumed to be a full-power mobile radio device operating in the licensed public safety portion of the 4.9 GHz band. Specifications for equipment will be derived from commercial 4.9 MHz products.

5.3. Hot Springs County JAN

A Hot Springs County JAN can be approximated using tower locations that already exist in the area. Towers within the WYOLink P25 network, the Hot Springs County Sheriff Department, and cellular networks are included in the scenario (refer to Figure 20). Note that this is only an approximation, created for the purpose of providing a baseline for the analysis.

While many of the WYOLink sites are outside of the county, all provide coverage to part of the county with the propagation characteristics of 700 MHz.

It is assumed that the tower sites are all on the EAN. This network provides better than broadband connectivity and will not be modeled.

Sample propagation studies have been performed for the tower locations. Table 5 gives the radio parameters for the studies. Radio network parameters will be studied in greater detail in the next section. For the propagation studies, refer to Figure 21 in 700 MHz and Figure 22 for 4.9 GHz.

Figure 20: JAN Tower Sites.

Table 5: Radio Network Parameters.

Parameter	IAN	JAN
Frequency Band	4.9 GHz	700 MHz
Channel Width	2 MHz	1 MHz *
Maximum Data Rate	3.0 Mb/s	1.2 Mb/s *
PSCD XMIT Power	0.25 watt	0.25 watt
PSCD Antenna Gain	3 dB	3 dB
PSCD Receive Sensitivity	-95 dBm	-95 dBm
Vehicle XMIT Power	1 watt/5 watts EIRP	25 watts/50 watts EIRP
Vehicle Antenna Gain	6.8 dB	3 dB
Vehicle Receive Sensitivity	-95 dBm	-95 dBm
Base Station Antenna Gain	8 dB	15 dB
Base Station XMIT Power	6.5 watts EIRP	250 watts EIRP
Base Station Receive Sensitivity	-95 dBm	-95 dBm

* Estimated based on FCC Report and Order No. 2

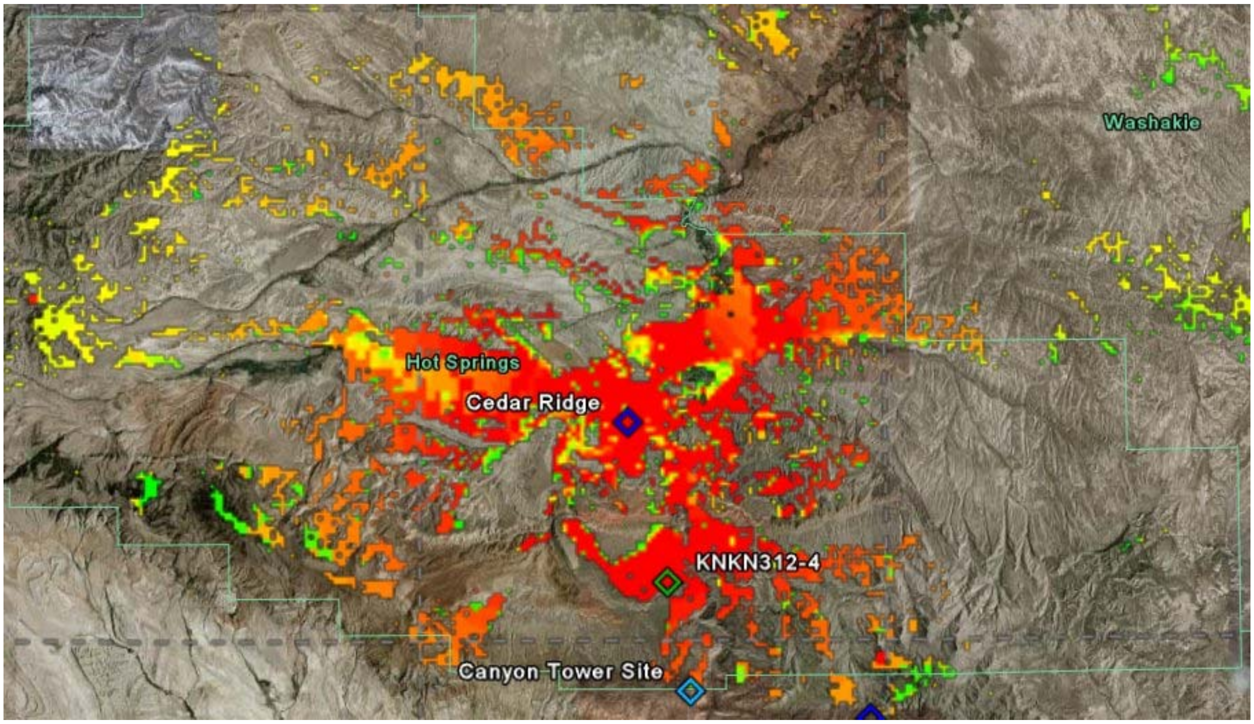

Figure 21: Example Coverage for a JAN 700 MHz Site.

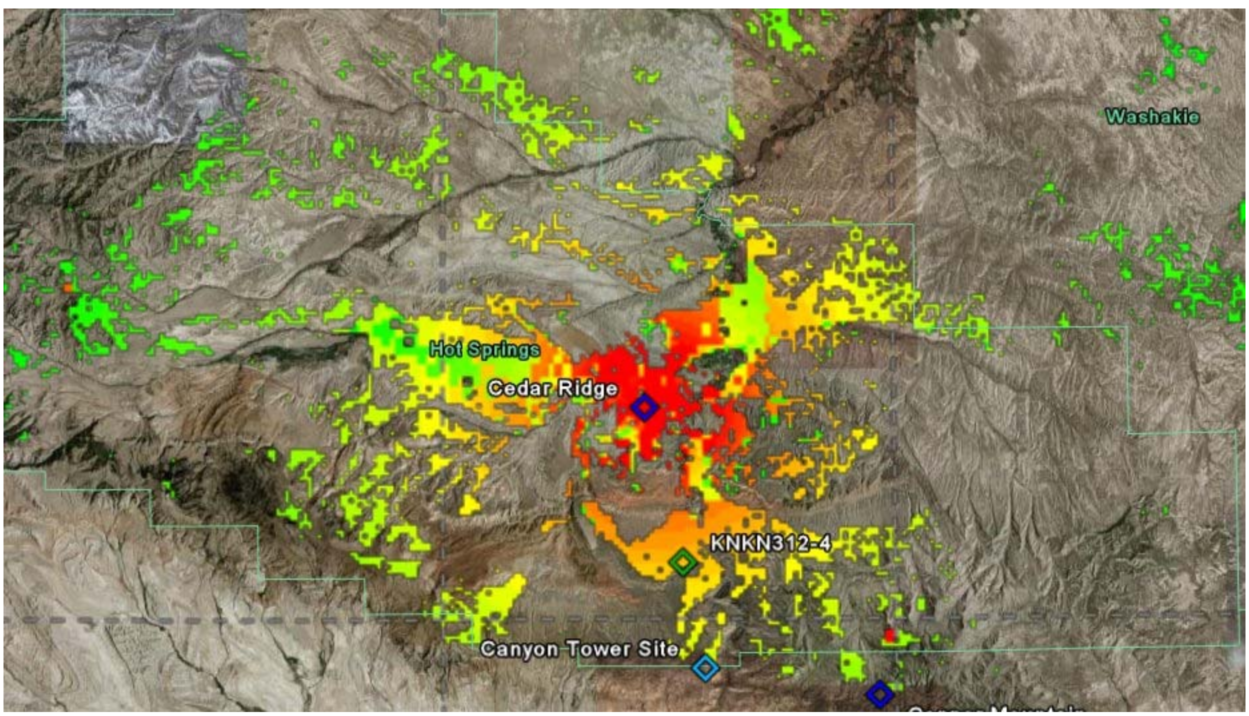

Figure 22: Example Coverage for a JAN 4.9 GHz Site.

5.4. Radio Frequencies, Digital Bandwidth, and Transmission Range

A major consideration of wireless data communication is the relationship between frequency and digital bandwidth, particularly with regard to the range (geographical coverage) of the various communication options, for point-to-multipoint communications. This document section reviews those considerations in Hot Springs County as they relate to the MANET project.

5.4.1. Frequency Considerations in Hot Springs County

Although certain frequency bands (e.g., the unlicensed ISM band) provide higher data-rate capabilities they also have tighter restrictions on transmitter output and radiated power, which limits system range. This paper section addresses these issues and suggests what should be considered in system planning.

Table 6 lists radio network assumptions based on FCC and/or typical equipment manufacturer data. For GHz systems we have used Tango Broadband point-to-multipoint systems, and for 700 MHz (except 700 MHz Broadband) and 900 MHz systems we have used GE MDS RF modem systems as examples. In the case of 700 MHz there are constraints due to limitations in the equipment that is currently available in the wideband (>64 kb/s) mode. (Note, also, that for 700 MHz the 12.5 dB gain omni base station antenna is approximately 23 feet long and weighs over 200 pounds.) For Table 6 we have assumed the base stations utilize omni antennas. For Table 7 we have assumed typical gain-oriented antennas, and flat panel antennas in the multi-GHz range. All plots are point-to-multipoint.

Table 6: Radio Network Assumptions—Omni Base Station Antennas.

Frequency Band	4.9 GHz	700 MHz	700 MHz Broadband*	900 MHz	900 MHz (ISM)	2.4 GHz (ISM)	5.8 GHz (ISM)
Bandwidth	2 MHz **	100 kHz	1 MHz	200 kHz	1.75 MHz	10 MHz	20 MHz
Data Rate	6 Mb/s	256 KB/s	> 1Mb/s	768 kb/s	1.2 Mb/s	5 Mb/s	10 Mb/s
Vehicle TX Power	0.24 W EIRP	2W EIRP	50W EIRP	2.5 W EIRP	1 W EIRP	0.4 W EIRP	4 W EIRP
Vehicle Antenna Gain	6.8 dB	3 dB	3dB	3 dB	3 dB	3 dB	6.8 dB
Vehicle RX Sensitivity	-90 dBm	-95 dBm	TBD	-92 dBm	-95 dBm	- 90 dBm	-87 dBm
Base Station TX Power	0.8 W EIRP	18 W EIRP	1kW/MHz EIRP	10 W EIRP	4 W EIRP	3.2 W EIRP	4 W EIRP
Base Station Antenna Gain	12 dB	12.5 dB	12.5 dB	9 dB	9 dB	12 dB	12 dB
Base Station RX Sensitivity	-90 dBm	-95 dBm	TBD	-92 dBm	-95 dBm	-90 dBm	-87 dBm
Bit error rate (BER)	10^{-5}	10^{-6}	TBD	10^{-6}	NA	10^{-6}	10^{-6}

Table 7: Radio Network Assumptions—Gain Oriented Base Station Antennas.

Frequency Band	4.9 GHz	700 MHz	700 MHz Broadband*	900 MHz	900 MHz (ISM)	2.4 GHz (ISM)	5.8 GHz (ISM)
Bandwidth	2 MHz **	100 kHz	1 MHz	200 kHz	1.75 MHz	10 MHz	20 MHz
Data Rate	6 Mb/s	256 KB/s	> 1Mb/s	768 kb/s	1.2 Mb/s	5 Mb/s	10 Mb/s
Vehicle TX Power	0.24 W EIRP	2W EIRP	50W EIRP	2.5 W EIRP	1 W EIRP	0.4 W EIRP	4 W EIRP
Vehicle Antenna Gain	6.8 dB	3 dB	3dB	3 dB	3 dB	3 dB	6.8 dB
Vehicle RX Sensitivity	-90 dBm	-95 dBm	TBD	-92 dBm	-95 dBm	- 90 dBm	-87 dBm
Base Station TX Power	0.8 W EIRP	31 W EIRP	1kW/MHz EIRP	39 W EIRP	4 W EIRP	4 W EIRP	4 W EIRP
Base Station Antenna Gain	21.9 dB	14.9 dB	14.9 dB	14.9 dB	14.9 dB	17 dB	17 dB
Base Station RX Sensitivity	-90 dBm	-95 dBm	TBD	-92 dBm	-95 dBm	-90 dBm	-87 dBm
Bit error rate (BER)	10^{-5}	10^{-6}	TBD	10^{-6}	NA	10^{-6}	10^{-6}

* Data based on ***estimated*** system specs from FCC 700 MHz Report & Order No. 2, released August 10, 2007.

** Two aggregated 1 MHz channels

Figure 23 is a Google Earth map of the area covered by the ComStudy radio propagation plots. It gives an idea of the irregular nature of the terrain surrounding Thermopolis. For each system approach, both for omni and gain-oriented (toward Thermopolis) configurations, propagation study plots are included in Figure 24 through Figure 37. In addition, Figure 38 is a propagation plot of the Sheriff's VHF hiband land mobile (voice) radio system assuming: 250 W EIRP Base Station transmit power, 9 dB gain omni antenna, 50 W mobile power and 3 dB gain mobile antennas.

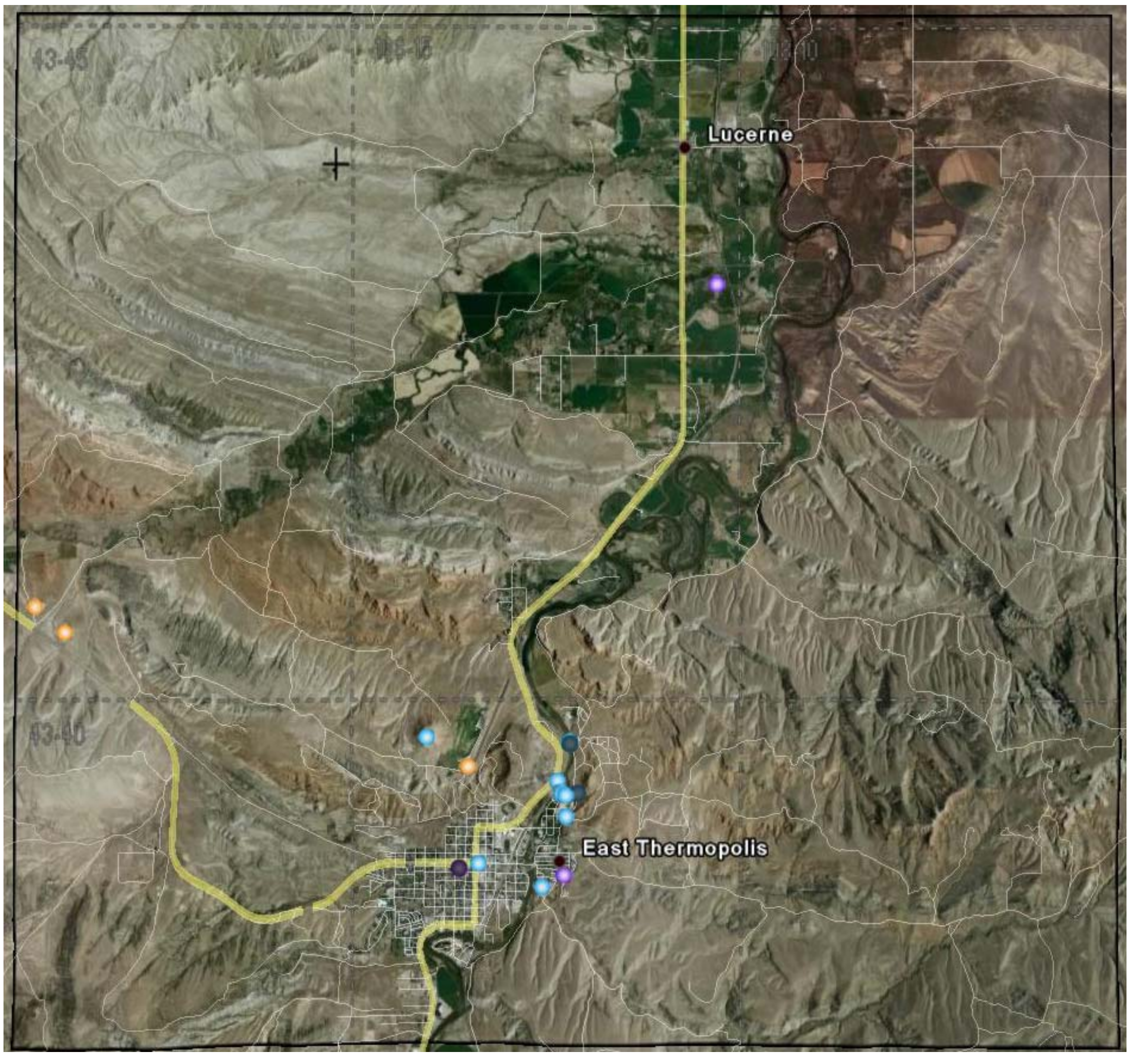

Figure 23: Google Earth Map of Thermopolis Wyoming.

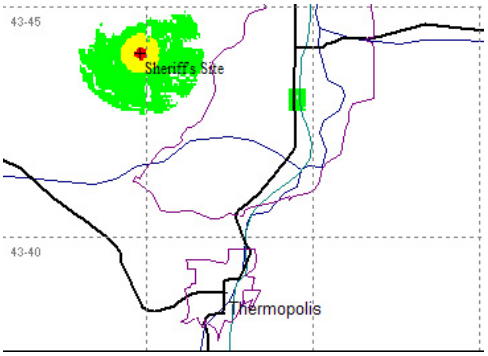

Figure 24: 4.9 GHz Omni

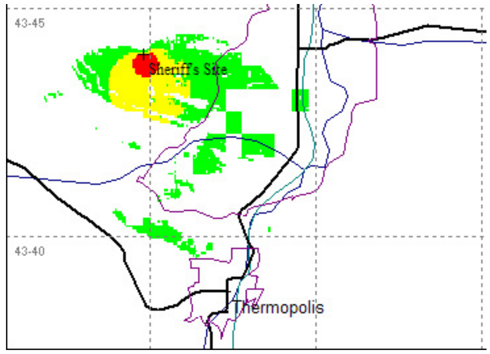

Figure 25: 4.9 GHz Gain Oriented

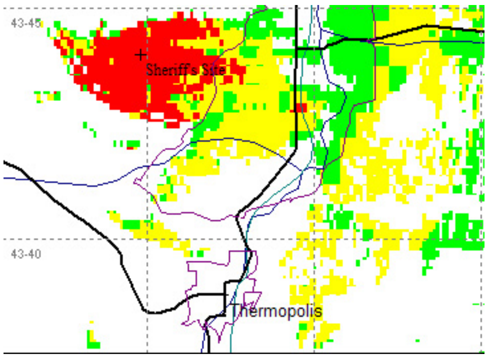

Figure 26: 700 MHz Omni

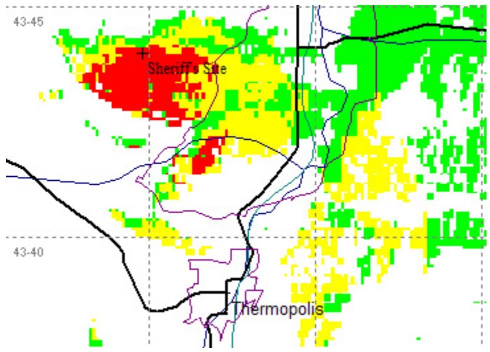

Figure 27: 700 MHz Gain Oriented

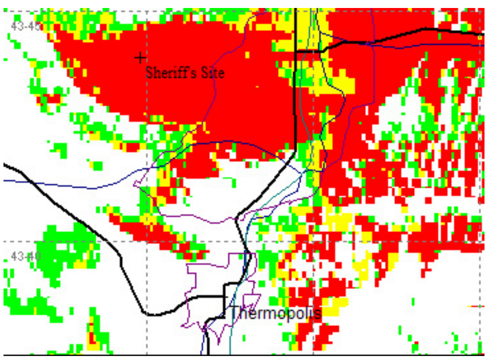

Figure 28: 700 MHz Broadband Omni

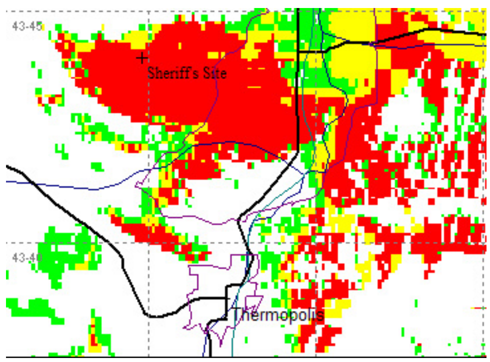

Figure 29: 700 MHz Broadband Gain Oriented

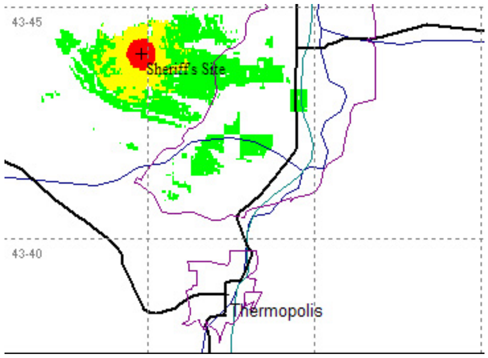

Figure 30: 900 MHz Licensed Omni

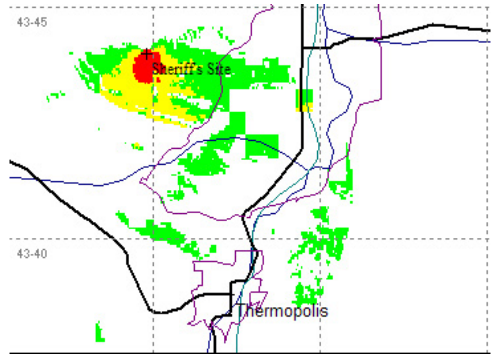

Figure 31: 900 MHz Licensed Gain Oriented

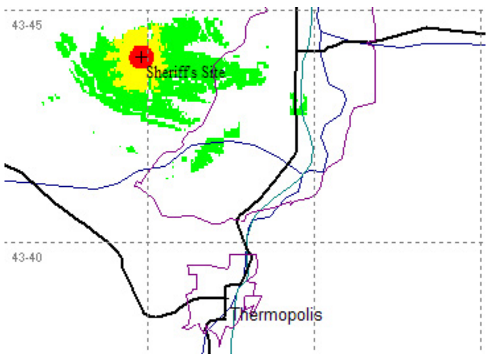

Figure 32: 900 MHz ISM Band Omni

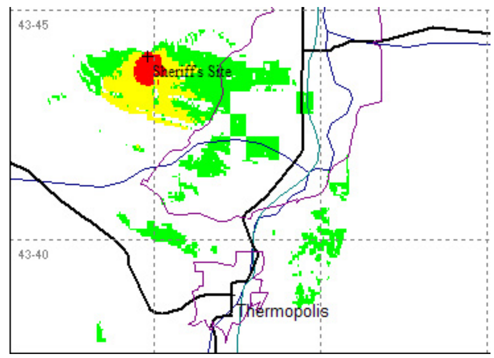

Figure 33: 900 MHz ISM Band Gain Oriented

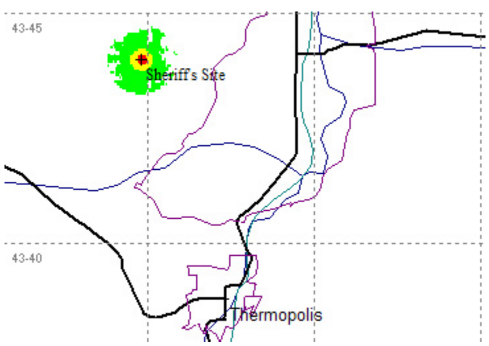

Figure 34: 2.4 GHz Omni

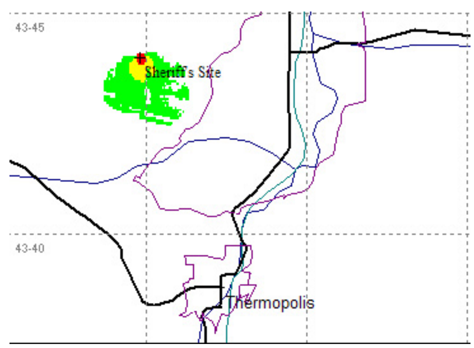

Figure 35: 2.4 GHz Gain Oriented

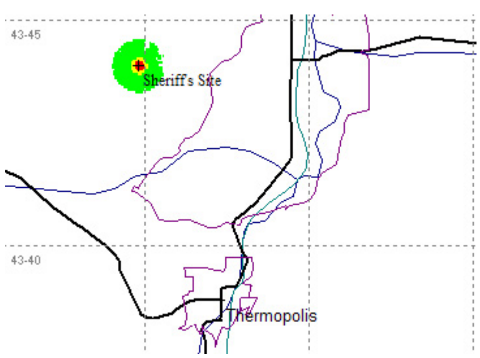

Figure 36: 5.8 GHz Omni

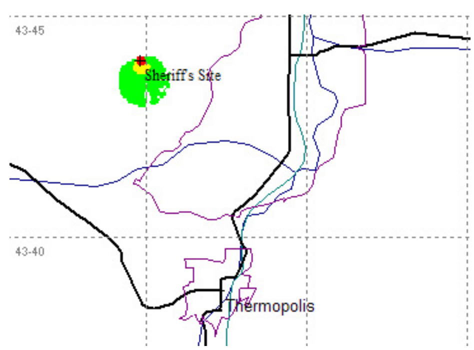

Figure 37: 5.8 GHz Gain Oriented

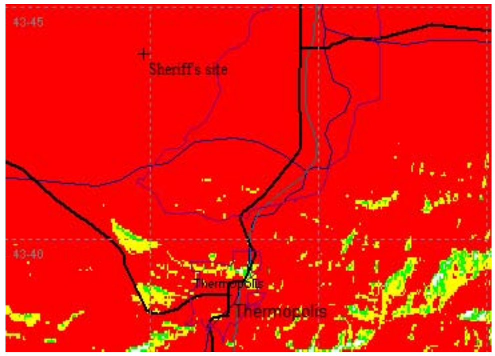

Figure 38: VHF Hiband Land Mobile (Voice)

For the licensed 700 MHz and 900 MHz frequencies, note that "talkout" (propagation coverage at the mobile receiver from base station transmission) and "talkback" (propagation coverage at the base station receiver from mobile unit transmissions) are very similar. This is due to the fact that higher transmit powers at the base station compensate for the lower antenna gain at the mobile. For 4.9 GHz (constrained by Tango equipment limitations) and the unlicensed 2.4 and 5.8 GHz systems this is not the case. Transmit power (EIRP) limitations at the base station, coupled with high-gain antennas that boost the received field strength, result in stronger "talkback." As an example we compare 2.4GHz talkout and talkback for this area in Figure 39 and Figure 40. Note, however, that whichever one has the least coverage is the one that must be used as a coverage plot to insure two-way communication. Hence, in the above figures only the talkout plots have been used.

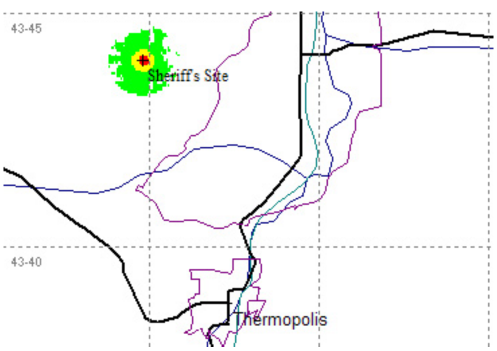

Figure 39: 2.4 GHz Omni Talkout

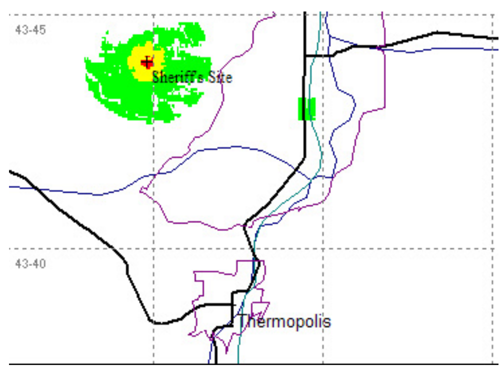

Figure 40: 2.4 GHz Omni Talkback

5.4.2. Antenna Patterns

Figure 41 and Figure 42 are the antenna patterns used in the propagation studies in this paper. The gain pattern is the actual pattern and orientation aimed from the Sheriff's RF site toward Thermopolis. Different gain figures were used for the different frequencies.

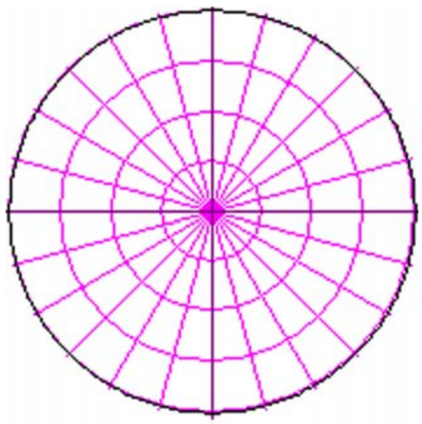

Figure 41: Omni Pattern

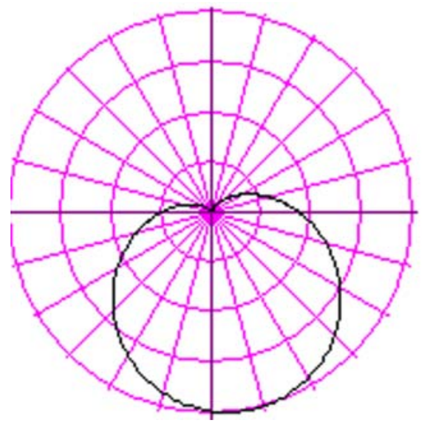

Figure 42: Gain-Oriented Pattern

5.4.3. Review of Frequency Related Limitations

The propagation studies reveal the constraints of high digital bandwidth and unlicensed (ISM Band) frequencies, particularly in the talkout mode in the 2.4 GHz and 5.8 GHz bands. These constraints are due to the transmit power limitations of ISM Band frequencies—multiple megabit digital bandwidth means limited range in this band. Hence, in system planning one must carefully determine the minimum digital bandwidth that can accommodate user requirements for data transmission. Table 8 shows FCC Public Safety 700 MHz Broadband Statement of Requirements, Version 6, dated November 8, 2007, regarding the forthcoming 700 MHz Broadband network, and shows preliminary data-rate limitations related to applications (e.g., file transfer, video, messaging, dispatch data, etc.). Table 8 also suggests appropriate data rates that will accommodate various user application requirements.

Table 8: FCC 700 MHz Data Rate Table

Public Safety 700MHz Broadband Statement of Requirements – Version 0.6

Application/Service	Description	Data Rate[7]
File transfer	i.e. to download such items as high-resolution images, GIS data, etc.	Greater than 256kb/s
Email		Less than 16kb/s
Web browsing		Greater than 32kb/s
Cellular voice	Analogous to today's cellular system capability.	4-25 kb/s
Push to talk voice	Analogous to commercial offerings, but coupled with group call capability.	4-25 kb/s
Indoor video	Indoor video is video that is transmitted from inside a building, whether it is surveillance or tactical video.	20-384 kb/s[8]
Outdoor video	Outdoor video is video that is transmitted from the street, whether it is surveillance or tactical video.	32-384 kb/s[8]
Location services	This includes location services for personnel as well as vehicles and other objects that public safety tracks.	Less than 16kb/s
Database transactions	This includes both remote databases (data that is not under the agency's direct control), as well as databases that are local.	Less than 32kb/s
Messaging	Instant messaging and SMS type services, both one-way and two-way.	Less than 16kb/s
Operations data	This is a catch all for data that deals with the operations and maintenance of the network, i.e. over the air programming, remote client management, etc.	Less than 32kb/s
Dispatch data	This area primarily covers data as it relates to computer aided dispatching.	Less than 64kb/s

[7] These figures are per application flow. These data rates will be updated over time as public safety's use of broadband matures.

[8] It has been noted that in order to meet public safety video quality needs, the data rate will likely need to exceed 64kbps.

Based on the plots above, the approximate line-of-sight range for the various frequency bands in this area of Hot Springs County is shown in Table 9.

Table 9: Approximate Line-of-Sight Range for Point-to-Multipoint Systems

Frequency Band	Range Omni	Range Gain Oriented	Typical Data Rate
4.9 GHz	5.5 mi	6.8 mi	6Mb/s
700 MHz	>10 mi	>10 mi	256 kb/s
700 MHz Broadband	> 15 mi	> 15 mi	16-384 kb/s*
900 MHz Licensed	5.2 mi	8 mi	768 kb/s
900 MHz ISM Band	4.6 mi	7.2 mi	1.2 Mb/s
2.4 GHz ISM Band	1.4 mi	2 mi	5 Mb/s
5.8 GHz ISM Band	0.8 mi	1.4 mi	10 Mb/s

*Depends upon application.

6. NOTIONAL NETWORK ROUTING REQUIREMENTS

6.1. Introduction

Providing responsive and effective public safety support requires effective coordination, command, control, and communication among various criminal justice and public safety agencies and public utilities [3, 24, 58]. These are particularly challenging in rural and sparsely populated areas, where the lack of communications infrastructure, large distances and difficult terrain adds additional difficulties and complexity. While considerable attention has been paid to public safety operations and interoperability in metropolitan regions, the less-populated rural areas remain underserved. The magnitude of this problem is demonstrated by the fact that 90 percent of U.S. law enforcement agencies serve rural areas, in locales with populations of less than 25,000 [25].

Despite their size, these small and rural law enforcement agencies face many of the same problems as their large urban and suburban counterparts. In fact, in terms of providing law enforcement services related to roadways, rural agencies conduct a large share of the response services: 78 percent of total roadway miles in the United States are rural (3,084,000 miles), 39 percent of vehicle-miles traveled are in rural areas, and 60 percent of crash fatalities occur on rural highways (23,876 fatalities in 2000) [26].

In terms of technology, rural law enforcement agencies tend to use, to be competently trained in, and to perceive as important a variety of communications-related technologies [25]. In other words, they have the equipment and understand its potential for improving public safety services, but are limited by the communications infrastructure. MANET provide the potential for addressing these pressing needs.

The public safety SoR defines a system-of-systems approach to providing robust, highly interoperable wireless communications. Figure 43 illustrates our understanding of a sample application of this network hierarchy to public safety needs.

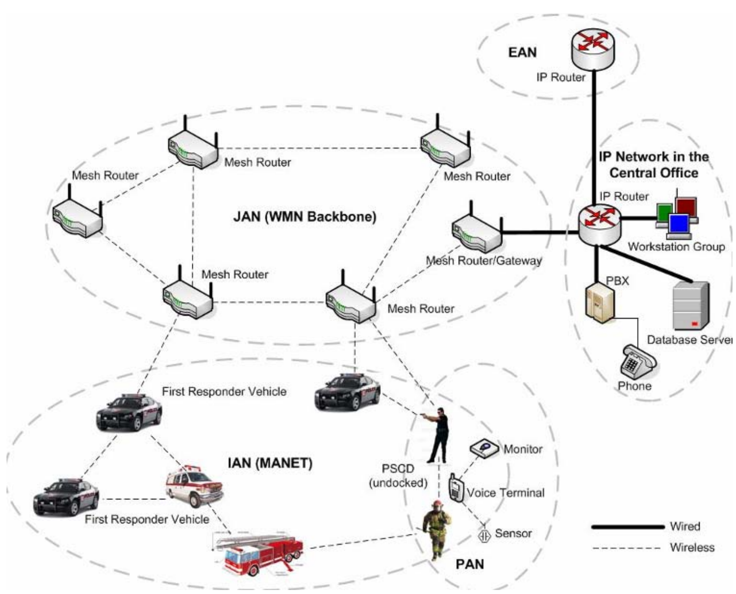

Figure 43: Example of a Public Safety System of Systems

Many of the concepts and components shown in this illustration have been developed and may be commercially available. The goal of this project was to develop standards-based, fully interoperable and highly robust methods of achieving the SoR objectives using emerging commercial approaches.

Routing is fundamental to meeting virtually all of the other requirements, and the overall goal of this project has been to develop a standardized routing protocol for MANET that meets the applicable requirements of the SoR and, in particular, addresses the challenges of implementation in remote rural locations such as Hot Springs County.

Our approach to developing notional requirements for rural areas has been multi-faceted, and includes:

- developing an in-depth understanding of the SAFECOM SoR,
- conducting a comprehensive review of the technical literature and standards activities associated with MANET, and
- working directly with the rural public safety community stakeholders to establish their operational needs and constraints.

The outcomes of each of these efforts are summarized below and incorporated in the notional routing requirements developed in this project.

6.2. Statement of Requirements Perspective

The SAFECOM program has developed and released documents that provide both qualitative and quantitative discussion of the requirements for communications and interoperability for the public safety community [3, 24, 58]. The notion of routing in these requirements refers primarily to the ability to assure that information arrives at its destination regardless of network conditions, which might include node mobility, high usage or congestion and node or link failures. The qualitative SoR specifies that to assure survivability, a protocol is required to assure that data is routing around a failed link in a personal area network (section 8.1.2.5, requirement no. 2), an incident area network (section 8.1.3.5, requirement no. 2), a jurisdiction area network (section 8.1.4.5, requirement no. 2), or an extended area network (section 8.1.5.5, requirement no. 2) [3, 58]. The quantitative SoR does not specifically address routing requirements, other than to indicate that routing functionality should be incorporated into nodes for relaying information (section 5.3.70) [24].

6.3. MANET Literature Perspective

MANET technology is rapidly evolving, with new standards and products entering the marketplace. There has been extensive research and technology commercialization in wireless networks, exploiting novel architectures, routing protocols and underlying physical layer technologies. Recent successes in ad-hoc and multi-hop networking have enabled a wide range of new applications including wireless LANs, personal area networks, home networks and sensor networks. A recent survey of wireless routing mechanisms lists over two dozen major protocol families, each of which has numerous variants [27], yet even this extensive study is considered incomplete. The intense level of activity in this area is driven by the diverse range of requirements and the practical realization that there is no universal optimum solution. In reviewing the literature and their own research, team members have found that there are numerous underlying assumptions in the design of wireless systems and the associated protocols [27]. In spite of these intense efforts, very little attention has been directed to addressing the problems imposed by public safety needs and rural areas. Several of the implicit assumptions and missing factors include:

- Line-of-sight communications between nodes is assumed.
- Real-time and prioritized service delivery has not been adequately treated.
- The network has a flat, non-hierarchical architecture.
- Links are persistent and performance is error-free.
- Single channel is used for communications.
- Terrain is uniform or irrelevant.
- There is always a connected path between source and destination.

Some or all of these assumptions are violated in rural, low-density networking environments. This research has sought to establish ways of addressing these specific problems and establishing mechanisms to use MANET to meet the stringent public safety features outlined in the SoR documents [3, 24, 58].

Specific technical challenges that were identified are:

- Most of current commercial MANET products use proprietary, non-standard routing protocols, which cannot satisfy all requirements stated in the SoR.
- The priorities influencing commercial MANET work are not congruent with public safety needs.
- Typical mesh network implementations do not support the range of service classes and do not satisfy all Quality of Service (QoS) requirements described in the SoR.
- MANET routing techniques do not fit readily with the system-of-systems architecture.
- Sparsely populated rural and remote areas require new approaches to MANET routing.

In addition, this research has found that there are numerous general challenges faced by public safety agencies for the operability and interoperability of their communications systems. Because of irregular terrain, VHF hi-band has been selected for public safety voice communication in states such as Wyoming and Montana to overcome the RF coverage limitations of higher frequencies. Other states such as Utah and California have implemented 800 MHz systems because of FCC designation of numerous frequencies in that band to public safety. Typically, UHF and higher frequencies may experience severe line-of-sight limitations. The FCC has recently opened a new spectrum in the 700MHz range for public safety and in the winter of 2008 held an auction to offer some of the spectrum on a national basis for a public/private partnership, with public safety usage having top priority and preemption privileges. This possibility prompted inclusion of the 700MHz spectrum and its coverage implications into the examination of notional requirements.

Systems may need to be operable in these licensed frequencies, but it might also be the case that unlicensed frequencies are usable under certain circumstances. Interoperability among jurisdictions at various levels is a non-trivial challenge, both technically and institutionally.

Furthermore, system cost is likely the biggest challenge faced by public safety agencies in implementing new technologies.

6.4. Rural Public Safety Stakeholder Perspective

Direct interaction and dialog with the rural public safety community has been a key component in the development of notional requirements. This project was structured to use Hot Springs County as a test bed for identifying specific rural public safety needs. Hot Springs County presents public safety officers with extreme versions of the challenges faced generally by public safety agencies in remote, rural areas—namely, lack of infrastructure, rugged terrain, low population, large area, severe weather, and limited resources.

As of 2003, the population of Hot Springs County was 4,665. Covering just over 2,000 square miles, Hot Springs County has a population density of barely 2.3 people per square mile. Two primary roadways cross Hot Springs County and intersect at the county seat, Thermopolis, to form a fork: Wyoming Route 120, which runs from Thermopolis to the northwest towards Cody, and U.S. 20, which runs through Thermopolis and the county from north to south. Hot Springs County includes both the Wind River Indian Reservation and the Shoshone National Forest; therefore, there are a number of local, state and federal government agencies that have jurisdiction over different areas. The Wind River Canyon, to the south of Thermopolis along U.S. 20, is particularly problematic in terms of communication. Canyon walls reach heights of more than 1,000 feet above the canyon floor and road below [2].

This phase of the project was conducted by meeting with Hot Springs County public safety officials, discussing particular public safety incidents, and maintaining an ongoing dialog with this public safety community with the Hot Spring County Sherriff's Office as the point of contact. The meeting held in Thermopolis in April 2007 was attended by representatives of the Hot Springs County Sheriff's Office, the Thermopolis police and fire departments, the Hot Springs County Fire Department, the Bureau of Indian Affairs, the National Forest Service, the State of Wyoming, local volunteer search and rescue groups and other public safety stakeholders. An illustration of public safety needs, derived from specific incidents, is illustrated in Table 10.

Table 10: Hot Springs County Public Safety Needs.

Incident Type	Traffic	Mobility	Network Size	Area Size
Wildfire (Black Mountain Fire)	Voice, Data, Video	One fire truck circles around the mountain and the other trucks and the first responders are almost stationary or move slowly	780 first responders and 5 vehicles	40mi x 50mi
Search & Rescue	Voice, Data, Video	Vehicles move at the speed of 20-25mph. Off-road driving and random movement.	40 first responders and 30 cars	5mi x 5mi
Crime Scene	Voice, Data	Vehicles move at high speed on the roadway	Varies	Varies
Flooding	Voice, Data	Vehicles move at the speed of 20-25mph along the riverside	10 vehicles	Very large
ID Checking	Voice, Data	Stationary or mobile	Single	Linear, along roadway.
Highway Patrol	Voice, Data	Stationary or mobile	Single	Linear, along roadway.

Common to all of these examples was a lack of adequate communications infrastructure, rural and remote incident locations, multiple agency engagement and challenges in interoperability and coordination.

6.5. Definition of Notional Requirements

These direct engagements with the rural public safety community, together with examination of the SoR documents and the publicly available literature, led to the development of five incident scenarios that have driven the definition of notional requirements and have served as the basis for protocol development, modeling, simulation and in-situ demonstrations for this project.

A template, shown in Table 11, was developed to capture the notional requirements of public safety networks. This template was used to capture the essential aspects of specific incidents and incorporate the key elements into scenario models for protocol analysis and evaluation.

Table 11: Template for Notional Requirements of Public Safety Networks.

Factor	Comments
Incident details	
Timeline of events	Includes details of the incident and the response
Telecommunications traffic	Voice, GPS-based location (AVL), e-mail, video, images, maps
Location	Fixed and mobile elements
Location of incident	Coordinates and extent
Start and end locations of participants	Vehicles and individuals
Speeds and travel times to intermediate locations	Trajectories
Incident area	
Network coverage	May include multiple networks
Topography	Include description of terrain
Participants	Textual description of role of participant, both responders and civilians
Network size	
Number of nodes	
Node types	Heterogeneous/homogeneous
Bandwidth	
Transmit power/receive sensitivity	
Node processing power	

The SoR and discussions with responders led to the identification of numerous communications applications and characteristics. To enable effective modeling and simulation and side-by-side comparison of results, three basic traffic flow types were defined to be used in conjunction with the notional requirements. The characteristics were defined using commonly assumed parameters based on typical standards and industry practices.

Table 12 summarizes the traffic flow characteristics. While there are numerous variations possible (e.g., voice can be compressed to less than 10 kbits/second, video can be transmitted at variable rates, etc.) these values broadly characterize the range of applications described by the public safety stakeholder community.

Table 12: Traffic Flow Notional Requirements

Traffic type	Packet size	Packets per second	Traffic demand	Standard
Video flow	6400 bits/packet	50 packets/second	323 kbits/second	Windows Mediaplayer
Voice flow	480 bits/packet	50 packets/second	24kbits/second	G.726
Data flow	1024 bits/packet	8 packets/second	8kbits/second	OPNET default value

7. MANET COMMERCIAL STANDARDS, ROUTING PROTOCOLS AND GAP ANALYSIS

7.1. Introduction

The topic of MANET is extremely broad, encompassing mobile nodes ranging from low-speed or stationary nodes (e.g., pedestrians) to moderate-speed vehicles (automobiles, trucks, etc.) to very high-speed helicopters and aircraft. For the purposes of this report, where the focus is on public safety personal area and incident area networks, we restrict the study to the low-speed and moderate-speed cases. This restriction naturally targets the study on the domain often defined as VANETs, or vehicular ad-hoc networks.

Vehicle communication networks are designed to provide drivers with real-time information through vehicle-to-vehicle or vehicle-to-infrastructure communications. Vehicle communication methods often rely upon the creation of autonomous, self-organizing wireless communication networks, or VANETs, designed to connect vehicles with fixed infrastructure and with each other. Research projects such as COMCAR [28] and DRIVE [28] have examined how vehicles in a network communicate with each other or with external networks, such as the Internet, through the use of communication infrastructure such as wireless cellular networks. Other projects, including FleetNet [29] and NoW (Network on Wheels) [30] have explored ad hoc network techniques.

Recent improvements in MANET technology and ever-increasing safety requirements as well as consumer interest in Internet access have made VANETs an important research topic. Vehicle-to-vehicle and vehicle-to-roadside communications have become important components of vehicle infrastructure integration. Most of the VANET research has focused on urban and suburban roadway conditions, where the numbers of vehicles are large, the inter-vehicle spacing is small, terrain is not a significant factor, and fixed communication infrastructure is available. In rural and sparsely populated areas, the conditions and constraints are significantly different. Node densities are low, inter-vehicle spacing can be large, terrain effects may be significant, and there is very little or no fixed communication infrastructure available. The coverage provided by wireless carriers is predominantly in urban areas and along major highways, not in rural areas and minor roadways. Although position awareness, based on GPS and other techniques, has becoming widespread in portable and vehicular systems, lack of infrastructure and terrain effects limit its availability and utility in rural areas. While public safety and other applications rely or benefit from position awareness, making this a requirement for routing places an unnecessary constraint on system design.

VANETs have particularly important applications in rural areas because of the lack of fixed communication infrastructure. VANETs in rural areas can be characterized as partially connected MANET with low node density and high node mobility. Routing algorithms appropriate for these circumstances have been less explored and the design of such a routing protocol is challenging.

In this report, we examine a range of VANET routing protocols and describe their main areas of application and their associated limitations.

7.2. Routing Protocols for VANETS

The general approach for information delivery in partially connected MANET is to relay messages hop by hop, not necessarily continuously but at discrete time intervals as links become available. Data may be stored in intermediate nodes for some time before it can be forwarded. With this message relay approach, data delivery may incur a long delay. In a fully connected MANET, if a route is found packet delivery will be accomplished in a relatively short time, determined by a combination of the propagation, processing and transmission delays.

The design of efficient routing protocols for VANETs is challenging due to the high node mobility and the movement constraints of mobile nodes. VANETs, as one category of Inter-Vehicle Communication (IVC) networks, are characterized by rapid topology changes and frequent fragmentation [31]. Conventional topology-based routing schemes are not suitable for VANETs. Reactive routing schemes will fail to discover a complete path due to frequent network partition and proactive routing protocols will be overwhelmed by the rapid topology changes and even fail to converge during the routing information exchange stage [32].

Position-based routing schemes generally require additional information on the physical position of the node during the routing decision process. A location service is needed as well to provide the node position information. Generally, location service is provided based on position information derived from GPS or other positioning systems. Broadcast protocols that make use of GPS information to improve the broadcast performance in IVC networks were proposed in [33].

Considerable work has been done using position-based routing for VANETs in the FleetNet and Network on Wheels projects. These efforts have included the development and evaluation of roadway mobility models and position-based routing techniques, and comparisons with topology-based protocols including DSR and AODV [34]. The results generally show excellent performance for position-based routing (e.g., high packet delivery ratio and low latency) relative to other protocols, but have been applied primarily to high node density conditions. Some work has been reported that addresses non-ideal wireless propagation, but does not include specific terrain effects [34]. Recent work to address terrain effects and assure quality of service for routing in remote areas for roadside-to-vehicle communications was recently reported in [35], where stationary nodes (access points) play a key role in route maintenance. This approach uses a predication algorithm to estimate the lifetimes of wireless links among moving nodes.

A multicast protocol for inter-vehicle geocast by defining a restricted broadcast group using GPS information was studied in [36]. Other inter-vehicle communication schemes using GPS information include [37]-[39]. In [37], a zone-of-relevance is defined based on the distance from a receiving node to a source node. In [38], by using GPS information, a spatially aware packet routing is proposed to predict the topology holes that might exist due to the spatial constraints of node movement. Intelligent opportunistic forwarding decisions using velocity information obtained through a GPS system are explored in [39].

A direction-oriented routing scheme for inter vehicle multi-hop wireless networks is proposed in [40], where the direction information of each node is exploited for routing decision. Relative speed-based routing for VANETs is proposed in [41], in which the relative speed and the cumulative change of the distance of a node to its neighboring nodes are used as the metrics to estimate whether a route is stable or not. Similarly, in [42], optimal hop selection in VANETs on highways was analyzed to maximize the expected route lifetime. These schemes and approaches are focused on the fully connected VANETs and are not appropriate for sparse, partially connected networks.

An ad hoc network that uses the generalized-message-relay approach is also called a Delay Tolerant Mobile Network (DTMN) [43]. Data delivery in partially connected ad hoc networks is generally based on the store-and-forward message relay approach [44]-[47]. A message-ferrying approach was presented in [45], where a set of special mobile nodes called message ferries move around the deployment area according to known routes while other nodes transmit data to distant nodes out of range by using the ferries as relays. A similar method is proposed in [46], where some nodes called “data mules” are used to collect data in a sparse sensor network. The sensor nodes are generally static, but the data mules are mobile. Another approach using message relay was proposed in [47], in which mobile hosts actively modify their trajectories to minimize the transmission delay when they transmit messages. All approaches mentioned above are mobility-assisted and proactive in nature since nodes modify their trajectories proactively to assist communication. However, it is not always the case that non-randomness in the movement of nodes can be exploited to help data delivery. Sometimes no mobile nodes can serve as “message ferries,” and there is generally no repetition in the individual node’s trajectory.

Epidemic routing was introduced as an alternative approach for partially connected ad hoc networks [48]. In that routing algorithm, random pair-wise exchanges of messages occur among proximate mobile nodes. The movement inherent in the nodes themselves is exploited to help deliver the data when a network is partially connected. The epidemic algorithm is flooding-based, and it trades system bandwidth and node buffer space for the eventual delivery of a message.

To control flooding or save system bandwidth and node buffer space, different flooding control schemes have been proposed [49]-[51]. However, these control schemes all assume that nodes have some prior knowledge or history information about other nodes. Probabilistic metric “delivery predictability” is explored in [49] to select the better next step candidates. The “delivery predictability” function is based on the history of encounters, assuming nodes know how many times they encounter other nodes. Similarly, a forwarding decision based on the “utility function” is proposed in [50], in which more information about other nodes, including the nodes recently noticed and the most frequently noticed, the power level, the rediscover interval etc., are used to calculate the utility function. An opportunistic exchange algorithm using a spatio-temporal relevance function to manage node buffer space was proposed in [51].

These flooding control schemes based on prior knowledge or history information about other nodes are not readily applicable for partially connected VANETs. The low node density, combined with the difficulty of obtaining the information used in the routing determinations limits the effectiveness of these schemes. Furthermore, the assumption that nodes will have GPS-based location information is an additional constraint and there may not be repetition in node trajectories as needed in some of the approaches. Terrain effects in mountainous areas make GPS-based location awareness problematic.

7.2.1. QoS Aware Routing

In [52], the authors propose a Stateless Wireless Ad Hoc Network (SWAN), which implements distributed network congestion control algorithms by probing local network conditions with broadcast packets, and marking traffic that experiences congestions. SWAN uses the measurements as feedback into its control systems, and is reactive to network congestion. In [53], the authors consider the 802.11e MAC layer, and control back-off times for each priority level of traffic using feedback from measured packet collision rates. In [54] the authors propose modeling the available bandwidth by passively measuring channel activity, using a model to proactively prevent network congestion in a mobile environment. In [55], the authors propose the CEDAR protocol, which they claim works with any on-demand routing protocol, by propagating link-state updates throughout the network. CEDAR is described more as a proactive routing scheme.

Research in MANET and VANET is ongoing. *Appendix – Recently Reported Results in MANET and VANET* Research provides an annotated list of recently published papers addressing these technologies.

7.3. Commercial MANET Products

There are very few commercial examples of MANET technology that are intended for the low and moderate mobility domain or environments where there is little or no existing communication infrastructure. The following provides a brief synopsis of several currently available mesh network solutions. Some are based on open source and standard protocols, while others are vendor specific and use proprietary technologies. These solutions have been designed primarily for metropolitan area applications, where the node density is high and the inter-node separation is typically small, so radio range is generally not a limitation. These examples illustrate the range of approaches under consideration and the diversity of application domains.

7.3.1. Roofnet

Roofnet was a project undertaken by the Computer Science and Artificial Intelligence Laboratory (CSAIL) at MIT in Cambridge, Massachusetts early in 2003. They managed to implement a campus-wide wireless network [56].

In about 2006, the city of Cambridge was trying to implement a similar system that would cover the entire city. Portland, Oregon, has taken the Roofnet idea and created a 70-node network in that city [57].

7.3.2. Tropos Networks

Tropos Networks is a company located in Sunnyvale, California. It is considered the market leader in delivering metro-scale Wi-Fi mesh network systems. It claims that its system is used by more major league baseball cities than all of its competitors combined, and that it also serves more than 30 countries.

Applications using Tropos systems include mobile Internet, residential and small business broadband Internet access, video surveillance, wireless meter reading, voice (Wi-Fi enabled phones), and multiple independent user communities on a single metromesh infrastructure.

7.3.3. PacketHop

PacketHop is a new company, founded in 2003, that is based in Silicon Valley, California. It develops software that creates instantaneous, self-configuring mobile mesh communications for several different market areas, including public safety agencies, commercial enterprises, and consumer markets. It also has software that allows devices such as laptops, tablet PCs, and smartphones to create portable networks that can operate both with and without access points. It undertook a different project in April 2007 when it teamed up with federal, state, and local first-responder agencies and provided the mobile broadband communications system for a full-scale Homeland Security Exercise & Evaluation Program (HSEEP). The exercise was mandated by the Federal Aviation Administration, and took place on April 22, 2006, at the Long Beach Airport. More than 28 agencies participated with over 400 first responders, to make it one of the largest Homeland Security training exercises ever conducted.

7.3.4. Firetide

Firetide is a California-based company that develops wireless mesh networks. Over half of Firetide's installations are video-based applications such as fixed wireless surveillance for high traffic areas in Dallas, crime deterrence in high crime areas (e.g., Rockford, Illinois, housing authority properties), covert surveillance for criminal investigations (Phoenix police department), and temporary surveillance networks (Texas State Fair). Firetide has outlined several factors that seem to be critical for ensuring successful implementation of its networks in the area of public safety: Investigate and draw from multiple sources of funding, address privacy concerns head on, and take steps to adopt guidelines and properly train personnel, anticipate staffing and training needs ahead of time, seek out system integrators and suppliers who are willing to "partner for success," and consider the total infrastructure and options for connecting the pieces together.

7.3.5. MeshDynamics

MeshDynamics is a company based in Santa Clara, California, that began developing mesh networks in 2002. It is now using Third Generation networks, which increase performance and decrease the problems that were inherent with First and Second Generation networks. MeshDynamics have had a great deal of success in cases where communities have tried other mesh network providers and have run into problems because their community requires multiple hops in the network. MeshDynamics networks don't appear to have as much trouble with multiple hops as others have, as demonstrated in places like central California farming communities and Red River, New Mexico. Its products are also being used by government defense and homeland security agencies to provide high quality video surveillance, especially where long distance feeds are necessary.

7.3.6. Strix Systems

Strix Systems has been named the worldwide leader in wireless mesh networking, both in market share and technology. A project it is implementing right now is to provide Brookline, Massachusetts, with a border-to-border wireless network for public safety data transmission. Stix claims that this project will replace a sub-standard cellular technology that city police and firefighters have put up with for years, and hopefully improve their ability to see to the safety of their city and its people. Another large project that it is working on now is covering Southern California's Coaster rail line. The rain line averages 48 passenger trains and two freight trains every day, and is the second most traveled rail line in the United States. The network will be put into place to improve security on the rail system with video surveillance and secured, encrypted communication methods to secure stations, tracks, bridges, and tunnels. The Department of

Homeland Security paid for this to be put into place on the Coaster rail line because it runs through Camp Pendleton, which is one of the largest Marine Corps bases in the United States.

7.3.7. Motorola

Motorola is another company that is working hard with public safety officials to implement effective wireless communication coverage. Ripon, California, is just such a community. Ripon was using a cellular service for its law enforcement providers, which only provided limited information in the field, but the service was recently dropped by the cellular provider. Ripon officials saw this as an opportunity to do better, and are working closely with Motorola to implement a wireless network that will maintain seamless coverage even while police are driving at top speed in chase situations. There will be 16 access points and 36 wireless routers to provide coverage to the nine-square-mile town, in addition to 81 client devices that can establish ad hoc network communications and integrate seamlessly into the infrastructure. Ripon officials are pleased because the establishment of the network has allowed their law enforcement agency to be much more effective without requiring them to add personnel.

7.4. Standards Activities

7.4.1. Dedicated Short-Range Communications

The primary work on standards associated with VANETs is being undertaken in the 802.11p working group. The IEEE 802.11p is a draft amendment to the IEEE 802.11 standard to add wireless access in the vehicular environment (WAVE). It defines enhancements to 802.11 required to support Intelligent Transportation Systems (ITS) applications. This includes data exchange between high-speed vehicles and between the vehicles and the roadside infrastructure in the licensed ITS band of 5.9 GHz (5.85-5.925 GHz). IEEE 1609 is a higher-layer standard on which IEEE 802.11p is based.

The 802.11p standard will be used as the groundwork for Dedicated Short-Range Communications (DSRC), a U. S. Department of Transportation project based on the European Communications, Air-interface, Long- and Medium-range (CALM) system looking at vehicle-based communication networks, particularly for applications such as toll collection, vehicle safety services, and commerce transactions via cars. The ultimate vision is a nationwide network that enables communications between vehicles and roadside access points or other vehicles.

The 802.11p Task Group is still active. Per the official IEEE 802.11 Work Plan predictions the approved 802.11p amendment is scheduled to be published in April 2009.

Most recently the European Commission has allocated the 5.9Ghz band for priority road safety applications and inter-vehicle, infrastructure communications. The intention is that compatibility with the United States will be ensured even if the allocation is not exactly the same; frequencies will be sufficiently close to enable the use of the same antenna and radio transmitter/receiver.

The main limitation of this effort is that there is no support for ad hoc or mesh networking. Also, the standard is designed for DSRC, a high-frequency, short-range wireless technology that is not well-suited for long range or rural environments where terrain is a major consideration.

7.4.2. WIMAX

WiMAX, or IEEE 802.16 is a new and promising wireless technology designed for both fixed and mobile applications. The initial 802.16d standard, released in 2004, targets fixed networks with point-to-multipoint topology. The more recently completed extension, 802.16e, is designed to support mobility, but is still optimized for point-to-multipoint topology. Both 802.16d and 802.16e include the possibility of mesh network support, but as yet this has not been exploited in commercial products. The principal WiMAX developments have been targeted to fixed networks (fixed wireless access and backhaul) and mobile point-to-multipoint applications. There is an effort currently underway in the 802.16j technical working group to define a relay node, which could enable mesh networks, but results are not expected until 2009 or beyond. Most of the current WiMAX products operate in either the unlicensed 5.8GHz range, or in licensed spectra at 2.5GHz and 3.5GHz (the latter not being available in the United States). There is discussion of new products targeted for the recently released 700MHz spectrum, but no announcements have been made to date.

7.5. Gap Analysis

This examination of the research, standards and products that are available to support VANETs and MANET indicates that there is no single product or emerging technology that meets the needs of public safety personnel in rural areas. Table 13 summarizes this assessment. The focus here is on the use of standards-based alternatives.

Table 13: Summary of Gap Analysis

Requirement	Assessment	Comment
Ad hoc topology support	Available in 802.11 standard, not 802.16	Effort underway to extend 802.16 to include mesh
Mobility support	Limited support in 802.11 (not intrinsic to standard); available in 802.16e	Overlays of 802.11 have evolved, but are proprietary
Quality of Service support	Available in 802.11e, but limited bandwidth, intrinsic to 802.16	Support offered at the link layer, not the network layer
Routing	Numerous proactive and reactive protocols available but don’t offer end-to-end QoS support	Existing QoS aware protocols do not make optimal route selections based on bandwidth and utilization

7.6. Conclusions

While there is extensive research interest in MANET, the area is still in its early stages with respect to commercial products. The currently available solutions rely largely on proprietary hardware and software. Furthermore, the underlying design considerations are not well matched to the requirements of rural public safety networks.

8. PROTOCOL DESIGN

8.1. Introduction

Providing responsive and effective public safety support is particularly challenging in rural and sparsely populated areas, where the lack of communication infrastructure, large distances and difficult terrain create complex difficulties. A MANET is a self-organizing, and highly dynamic wireless network composed of mobile nodes. Such a network can be formed on the fly without requiring any fixed infrastructure, and each node can act as a router to forward packets for other nodes. MANET are considered a promising solution for connecting vehicular and hand-held nodes with fixed infrastructure and with each other for public safety communications in rural areas. According to the SoR [58], public safety communications have stringent end-to-end Quality of Service (QoS) requirements that have not been adequately addressed by any standard ad-hoc routing protocols. Even though ad-hoc routing protocols vary in many respects, such as route discovery mechanisms (reactive vs. proactive), routing approaches (source routing vs. hop-by-hop routing), they share a common feature—a single, shortest path from the source node to the destination node is selected for packet forwarding. A shortest path may be a cost-efficient solution; however it may not be able to satisfy the end-to-end QoS requirements. For example, a heavily loaded node without enough available bandwidth may still be blindly chosen by the routing protocol for packet forwarding.

In this report, we explore the feasibility of using MANET for rural public safety. First, we discuss a QoS enhancement to a standard routing protocol, Dynamic Source Routing (DSR) [59]. Specifically, we introduce a new routing metric that offers full consideration for available bandwidth, delay and node mobility. By incorporating the routing metric and the bandwidth and delay estimation algorithms proposed in [60] ([61] with DSR), we designed a new routing protocol, QoS Aware Source Routing (QASR), to meet the QoS requirements specified in the SoR. For evaluation purposes, we present four scenarios—a river search, a hazardous materials spill, the Black Mountain Fire, and a dam breach—to model the rural public safety communication environment including the effects of terrain, node mobility and traffic patterns. We then evaluate the performance of QASR and the well-known standard routing protocols including Ad-hoc On-demand Distance Vector (AODV) [62] and DSR based on these benchmark scenarios using OPNET modeler [63] at the 4.9 GHz public safety spectrum band and at other frequencies. To our best knowledge, this is the first work to address ad-hoc routing in the context of rural public safety communications and evaluate different ad-hoc routing protocols based on real-life scenarios via extensive OPNET-based simulations.

8.1.1. Related Work on Routing Protocols

Routing is a fundamental problem in MANET. Four routing protocols have been standardized in the IETF MANET group, including AODV [62], DSR [59], Optimized Link State Routing (OLSR) [64] and Topology Dissemination Based on Reverse-Path Forwarding (TBRPF) [65]. Two other routing protocols, Dynamic MANET On-demand (DYMO) Routing [66] and OLSRv2 [67], are still Internet drafts. Standard ad-hoc routing protocols can be divided into two categories: reactive (on-demand) and proactive. On demand routing protocols will flood route discovery messages upon arrival of a connection request. The on-demand routing protocols include AODV, DSR and DYMO. Proactive routing protocols require the nodes to respond to changes in network topology by broadcasting updates throughout the network. OLSR and TBRPF fall into this category.

Supporting end-to-end QoS in MANET is very challenging. The AODV protocol has been extended to support QoS in MANET [68]. A resource reservation based routing and signaling protocol, Ad-hoc QoS on-demand routing (AQOR) has been introduced in [69]. In [61], Yang and Kravets presented a novel joint admission control and rate policing protocol, Multi-Priority Admission and Rate Control (MPARC) for MANET with multi-priority traffic. They also proposed a new protocol, Distributed Delay Allocation (DAA) in [60], which provides average delay guarantees for real-time multimedia applications in MANET. The available bandwidth and delay estimation algorithms introduced in [60], [61] are used in our routing protocol to enable QoS support.

8.2. QoS Enhancement

In this section, we discuss a QoS enhancement to DSR. The objective is to find a source-to-destination path that can satisfy the end-to-end bandwidth and delay requirements given by any incoming connection request. In addition, admitting a new connection request cannot disrupt any existing flows.

We designed our QoS-aware routing protocol, QASR, based on DSR. DSR is selected as the basis for QoS enhancement because according to DSR, the whole routing path is included in each data/control packet, which is necessary for end-to-end available bandwidth and delay estimations. In QASR, an available bandwidth estimation algorithm in [61] and a delay estimation algorithm in [60] are incorporated with the route discovery process of DSR. After the route discovery, if a set of feasible paths can be found, the destination node will select the path with the minimum cost based on a routing metric (which will be introduced later), and send a Route REPlay (RREP) message back to the source node along the discovered path in the reverse direction. However, if no feasible path is available, the connection request will be rejected. We focus on the Enhanced Distributed Coordination Function (EDCF) specified by IEEE 802.11e [70], which extends original Distributed Coordination Function (DCF) defined in the IEEE 802.11 standard to support service differentiation and QoS. In EDCF, traffic is divided into several classes and different classes are assigned different transmission parameters such as contention window size. Similarly, traffic is divided into six classes according to the SoR for public safety communications [58], which can be naturally supported by EDCF.

The estimation algorithms presented in [60], [61] are employed in QASR since they are considered as the best-so-far solutions for available bandwidth and delay estimation in a multihop wireless network with multi-priority traffic. These algorithms are essentially 2.5 layer algorithms that provide the QoS estimation information to the routing protocol according to the MAC protocol behavior and current traffic load. Bandwidth and delay estimations are very challenging in an 802.11-based multihop wireless network. Due to the impact of interference in a particular node v, any transmissions in its interference neighborhood may consume its available bandwidth; moreover, for a particular packet, node v may need to back off and re-transmit it multiple times, which leads to a long delay. In [61], a novel bandwidth allocation model was introduced to capture bandwidth sharing between competing flows in all possible network states. Based on the model, an algorithm was designed to estimate the available bandwidth for a node based on its state (including traffic load, traffic priority, contention window size, etc.) and the states of all nodes in its interference neighborhood. Similarly, a mathematical model and a closed-form equation were presented to accurately estimate the packet delay for a node [60] according to the node state information in its neighborhood. Due to space limitations, we omit the details of these two algorithms.

As mentioned above, a node's available bandwidth and the packet delay are related to its neighboring nodes in the interference range in a wireless environment. Therefore, in order to precisely predict the available bandwidth and delay, each node needs to collect the state information from all the nodes in its interference neighborhood periodically. The broadcasting period was set to 5s in the simulation. Since the interference range is usually two or three times the transmission range, it is not sufficient for a node to only broadcast its state information to its direct neighbors. In QASR, if each node has a GPS device (this is a reasonable assumption for public-safety-related mobile nodes), each broadcasting message will include the location of the node that generates this message. Once a node receives a broadcasting message, it will check its distance from the node generating the message. If it is no more than the interference range, it will re-broadcast the message. Otherwise, the message will be dropped. However, if the location information is not available, such messages will be broadcast within a two- or three-hop neighborhood. The control overhead can be reduced by using a randomized optimization scheme to select a subset of nodes in the interference neighborhood to rebroadcast the message. In this scheme, whenever a node in the interference neighborhood receives the message, it generates a random number and compares it with a given threshold. If the random number is larger than the threshold, the node will re-broadcast the message in the current period. Otherwise, it will stay silent.

A new routing metric is defined for route selection, which is the weighted sum of estimated available bandwidth, estimated delay and node speed. The cost of a node v is given by equation (1).

$$\text{cost(v)} = \alpha \frac{B - A_v}{B} + \beta \frac{D_v}{D} + \gamma \frac{S_v}{S} \quad (1)$$

In this equation, Av is the estimated available bandwidth and B is the channel capacity. Estimated delay Dv is normalized by a delay tolerance D and the average speed Sv is normalized by a maximum speed S. The values of B, D, and S may vary in different scenarios and different network environments. They were set to 750kbps, 50ms and 27mph respectively in our simulation. These parameters are then mixed by the coefficients α, β and γ, where $\alpha + \beta + \gamma = 1$. α, β and γ are tunable parameters which are used to scale the relative weight of each term in the metric. In the simulation, α=β=γ=1/3. Essentially, the cost of path is given by the sum of the costs of all nodes in the path. According to this metric, the mobile nodes with relatively large available bandwidth, a small packet delay and low mobility are more likely to be selected as relay.

Similar to DSR, QASR initiates a route discovery process by flooding Route REQuest (RREQ) messages when a node has data to send. Moreover, it will start a timer. When the timer fires, the connection request will be rejected if no RREP message is received during this period. Otherwise, the source node will start data transmission along the route included in the received RREP message. When an intermediate node v receives a RREQ message, it will discard this message if its estimated available bandwidth is smaller than the bandwidth requirement or the cumulative delay of the partial path from source to node v is already larger than the delay requirement. However, if the requirements are not violated and the cost of the partial path included in the message is smaller than the current minimum cost stored in v (which is initialized to 1 and is updated every time there is an improvement), the RREQ message will be re-broadcast. In addition, after the first RREQ message arrives at the destination, it will open an acceptance window, a time duration in which RREQ messages generated for that connection request will be collected. At the expiration of the acceptance window, the destination node will then select the best path from the set of feasible paths and reply with an RREP message.

8.3. Protocol Requirements Summary

In the MAC layer, Enhanced Distributed Coordination Function (EDCF) specified by IEEE 802.11e [70] is assumed to be used for medium access. EDCF extends the original Distributed Coordination Function (DCF) defined in the IEEE 802.11 to support service differentiation and QoS. After receiving a frame from the higher layer carrying its user priority, the EDCF maps it into an access category. Each access category has a different priority of access to the wireless medium, which is achieved by assigning different values for the access parameters such as contention window size. EDCF supports a total of eight access categories. Similarly, traffic is divided into six classes according to the SoR for public safety communications [58], which can be naturally supported by EDCF.

As mentioned before, DSR is selected as the basis for the development of QASR. According to DSR, the whole routing path is included in each data/control packet, which is necessary for end-to-end available bandwidth and delay estimations. However, the other routing protocols such as distance vector based routing protocol AODV, usually maintain a routing table in each node which only specifies the next-hop node for each possible destination. In this case, it is hard to make a precise estimation for the end-to-end performance.

The node location information is certainly preferred for routing operations such as information exchange. However, it is not necessary.

9. PROTOCOL EVALUATION

The enhanced protocol was modeled using OPNET and compared against other routing protocols (AODV and DSR). Scenarios were implemented within OPNET, and features such as terrain and mobility were incorporated.

9.1. OPNET Model

9.1.1. OPNET Model

The simulation environment used to model the protocol behavior and construct scenario configurations was OPNET 12.1 [1], a commercial network communications simulator. OPNET allows for scenario modeling with mobility terrain considerations on the wireless communications process. The OPNET Wireless modules were used, and the 802.11 node models were adapted to include the functionality required to implement a simulation of QASR. The other routing protocols (AODV and DSR) were already available in the standard OPNET configuration files. The OPNET terrain modeling module was used to incorporate the terrain of the study areas and to calculate path loss, terrain blockage and other propagation effects included in the Longley Rice model.

Key OPNET MANET model parameters are summarized below.

- Channel Bandwidth (QASR): 750 kbps
- Delay Limit (QASR): 50 ms
- Speed Limit (QASR): 27 mph
- PORC Constant (QASR): 3
- KB (QASR) 1/3
- KD (QASR) 1/3
- KS (QASR) 1/3
- Intermediate Node Buffer Size (DSR/QASR/AODV): 10 packets
- Allowed Hello Loss (AODV): 1
- Max Maintenance Retransmit (DSR/QASR): 2
- Maintenance Holdo_ Time (DSR/QASR) 1:0 sec
- Delay QoS Tolerance (DSR/QASR/AODV): 50ms
- Jitter QoS Tolerance (DSR/QASR/AODV): 50ms
- Radio Transmit Power (DSR/QASR/AODV): 5mW
- Radio Interference Range (DSR/QASR/AODV): 1500M
- Channel Bitrate (DSR/QASR/AODV): 1Mbps

The link layer used is the 802.11e MAC. The traffic demand is balanced over the top three 802.11e priorities, known collectively as the Realtime priorities. The lowest priority, known as the Background priority, is not used.

Each of the scenarios described below was incorporated into OPNET project models by developing trajectory files for each of the nodes, and overlaying the trajectories on terrain data maps obtained from the USGS.

9.1.2. OPNET Model Specifics and Customization

The standard wireless node models and protocols in OPNET Modeler 12.1 [63] were customized to meet the MANET project objectives and used to model the protocol behavior and construct scenario configurations. The MANET workstation model in the Modeler was chosen to model the vehicular and pedestrian nodes, which is shown in Figure 44. In the figure, the node model consists of multiple process models, each of which corresponds to a protocol in a particular layer. For example, the “ip” process model implements IP and the “wireless-lan-mac” process model implements the MAC protocol defined by the IEEE 802.11[70]. The OPNET Modeler includes implementation of most of standard routing protocols. Every ad-hoc routing protocol is implemented as a process model. One of the attributes of the node model is “Ad-Hoc Routing Protocol” which can be set to a standard ad-hoc routing protocol such as DSR, AODV and so on. For example, if it is set to DSR, the process model implementing DSR will be loaded to the modeler to find and maintain routes in the runtime. We implemented the bandwidth and delay estimation algorithms and inserted the corresponding procedures into the DSR process model. We also made a few modifications to the original implementation of DSR as described above. The “manet_rte_mgr” model serves as an interface between the process model corresponding to a routing protocol and the IP process model, which can be used to manage the statistics for simulation runs.

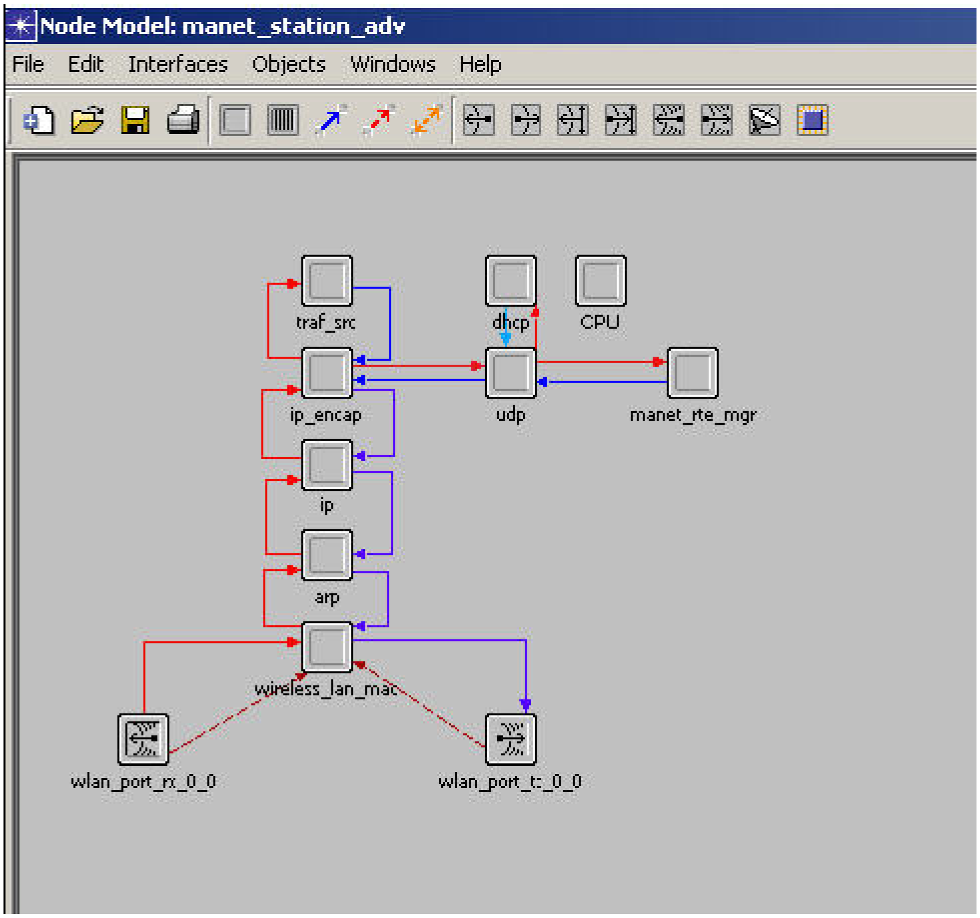

Figure 44: The MANET Workstation Model.

We also built up the public safety scenarios in the OPNET Modeler. As described before, each scenario specification includes the initial locations and moving trajectories and communication traffic demands for all the nodes in the network. For each scenario, we included longitude, latitude, height, moving trajectory and other related information of each node in a XML-based trajectory file. An example entry in a trajectory file is given as follows: "-108.20888, 43.654, 2, 0h2m13s, 0h0m0.0s, 0.000, 0.00, 0.000", which indicates that the corresponding node starts at the location with a longitude of W108.20888, a latitude of N43.654 and a height of 2 meters, takes 2 minutes and 13 seconds to reach the next position (which will be given by the next entry), waits at current position 0 second, and pitch, yaw, roll 0 degrees. The trajectory file should be imported into the OPNET Modeler before the simulation run. After the import, a network will be automatically set up and the nodes in the network will move as specified by the trajectories when the simulation starts. In order to accurately simulate the environment of rural public safety operations, a contour map from NASA was loaded to the OPNET Modeler to provide necessary terrain information. Figure 45 shows the contour map (red curves) and moving trajectories of nodes (white curves) corresponding to the river search scenario. In the simulation, the transmission power of each node was set to 5mW. The Enhanced Distributed Coordination Function (EDCF) defined in the 802.11e [70] was used as the MAC protocol. In addition, for traffic generation, the source-destination pair of every flow is also part of the scenario specification. The communication traffic included video flows, voice flows and data flows. The video flows are MS media player based video streams with a mean data rate of 320kbps [71], the voice flow is G.726-based Voice-over-IP (VoIP) streams with a constant data rate of 24kbps [72] and the data flows have a mean data rate of 8kbps. There are three priority levels, high, medium and low. The priority of each flow was randomly selected. For the high priority flow, both the delay and jitter tolerances were set to 50ms [58]. Simulation runs were conducted to study the protocol behaviors on multiple spectrum bands including the ISM band at 2.4GHz (since most of previous research on ad-hoc routing focuses on this spectrum band), the public safety communication band at 4.9GHz and the recently allocated public safety communication band at 700MHz.

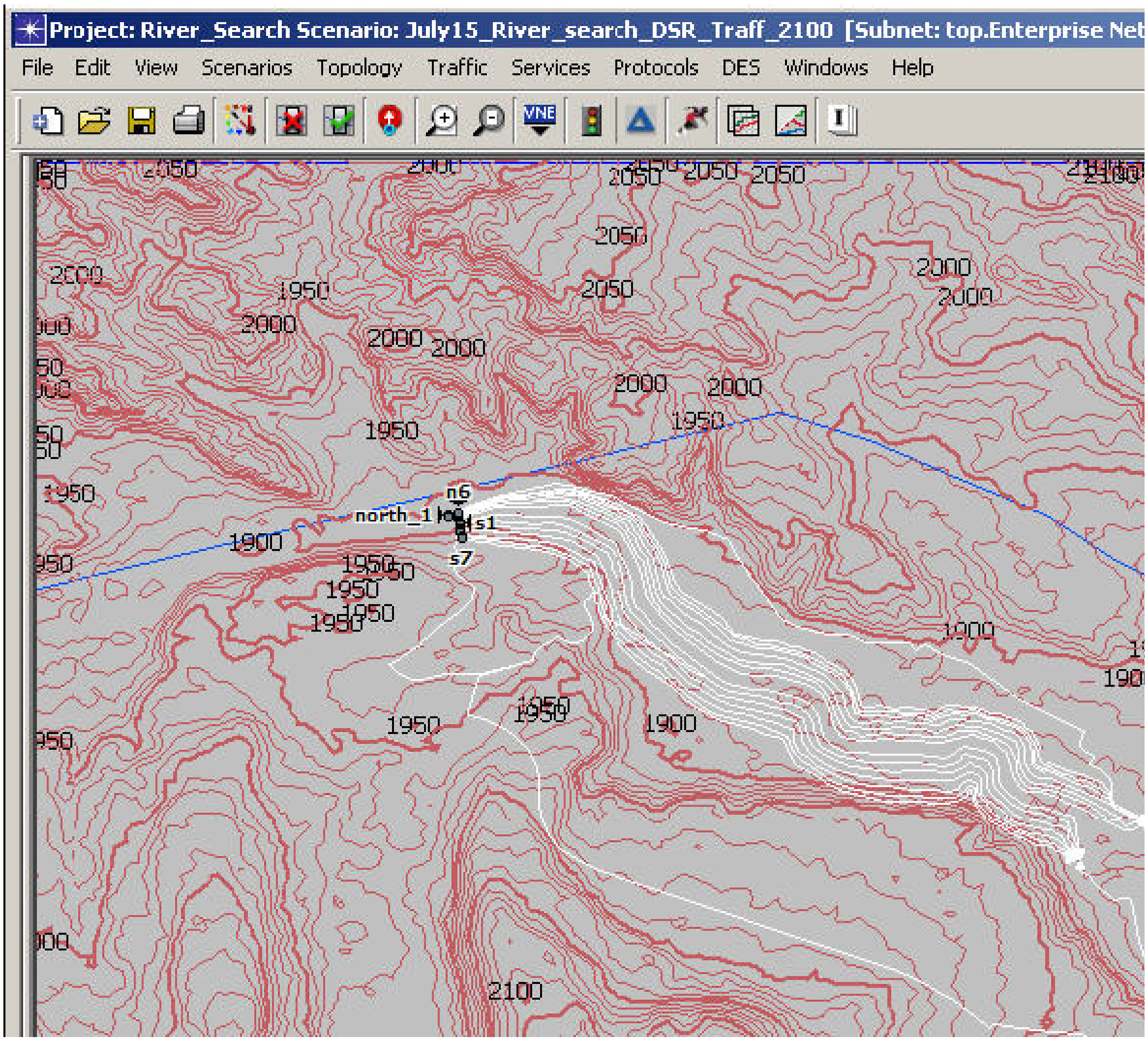

Figure 45: The Contour Map and Trajectories Corresponding to the River Search Scenario.

9.2. Rural Public Safety Scenarios

In this section, we briefly describe the four public safety scenarios used to test the performance of QASR in comparison with DSR and AODV in rural environments with irregular terrain. The details of the scenarios are provided elsewhere in the report. The scenarios were developed according to actual rural communication problems obtained through discussions with public safety officers, and the actual terrain and roadway information given by USGS survey [73] and Google Maps [74], respectively. OPNET Modeler 12:1 [63] was used to model the protocol behavior and construct scenario configurations. The scenarios include trajectories for vehicle and pedestrian mobile nodes, location information and communication traffic associated with voice, video and data applications. A brief introduction for the four scenarios follows:

1. The river search scenario represents a coordinated search along the Wind River (30km southeast of Dubois, Wyoming) for a missing person. The river valley is 1.6km across at its widest in the context of our simulation. Nodes in the network represent both rescue workers on foot walking along the river bank in the valley, as well as vehicles that maneuver along the adjacent roadways to overlook the search effort by visually monitoring the health and safety of the rescue workers. The terrain within the river valley causes blockage and intermittent connectivity for communication among nodes in the valley. The over-watch vehicle nodes are often positioned as relays to enable additional routes between rescue worker nodes. In this scenario, the traffic is generated by 16 nodes with 28 flows between various members of the search party.

2. The dam breach scenario represents a coordinated effort to warn residents of Thermopolis, about 30km downstream of a reservoir on the Wind River, of an imminent flood due to the catastrophic breach of the dam. In this case, mobile nodes systematically drive along the city streets, communicating with each other and with a few fixed nodes located at the Sheriff's office and disaster control center in the police station. The model includes the grid of streets to define the node trajectories. Different from the river search scenario, the nodes in the network are connected most of the time in this scenario. In addition, the traffic is generated by 23 nodes with 22 flows between police vehicles.

3. The Black Mountain fire scenario represents an extensive effort to contain a forest fire that spread over a large area. The responders consisted of four fire trucks, eight firefighters, two sheriff's cars and a pumper truck. Pairs of firefighters are associated with each fire truck, and the sheriff's cars are in communication with each other, as well as a second sheriff providing connectivity to the fire trucks and pumper truck. The responders are in clusters, and there is high mobility. Due to the large area, the sheriff cars act as relays, as the fire trucks are too far apart to communicate directly. The overall duration of the scenario is four hours, six minutes.

4. The HAZMAT spill scenario represents a response to a hazardous waste spill along a rail line, where responders move about in the spill area. There are 16 nodes and the duration of the scenario is three hours.

In these scenarios, the networks were operated at the 4.9GHz public safety spectrum band as well as at other frequencies including 2.4GHz, 900MHz and 700MHz, and the transmission power of each node was set to 5mW. The EDCF defined in 802:11e [70] was used as the MAC protocol. In addition, for traffic generation, a pair of source and destination nodes was specified by the scenarios for each flow. The communication traffic included video flows, voice flows and data flows. The video flows are MS media player video streams with a mean data rate of 320kbps [71], the voice flow is G:726-based Voice-over-IP (VoIP) streams with a constant data rate of 24kbps [72] and the data flows have a mean data rate of 8kbps. There are three priority levels—high, medium and low. The priority of each flow is randomly selected. For the high priority flow, both the delay and jitter tolerances were set to 50ms [58].

9.3. Baseline results

The following subsections provide further detail on each scenario and baseline results using standard routing protocols DSR and AODV. In each scenario, simulations were carried out at 4.9GHz, 2.4 GHz, 900MHz and 700MHz to determine throughput, averaged over the entire duration of the scenario. This first set of simulations was carried out using both line-of-sight (LOS) and Longley-Rice propagation models using the DSR routing protocol. The next set of simulations examines the performance using DSR and AODV routing protocols, assuming Longley-Rice propagation at 700MHz. We emphasized the use of 700MHz as the propagation characteristics at this frequency yield longer range and the 700MHz band is now available for public safety applications due to recent FCC activities to reallocate spectrum. Results using QASR and comparisons of QASR with the standard protocols are provided later.

9.3.1. River Search Scenario

NUMBER OF NODES:

16 NODES: South_1, North_1, n1, n2, n3, n4, n5, n6, n7, s1, s2, s3, s4, s5, s6, s7

LENGTH OF SCENARIO

49 minutes

COMMUNICATION HIERARCHY

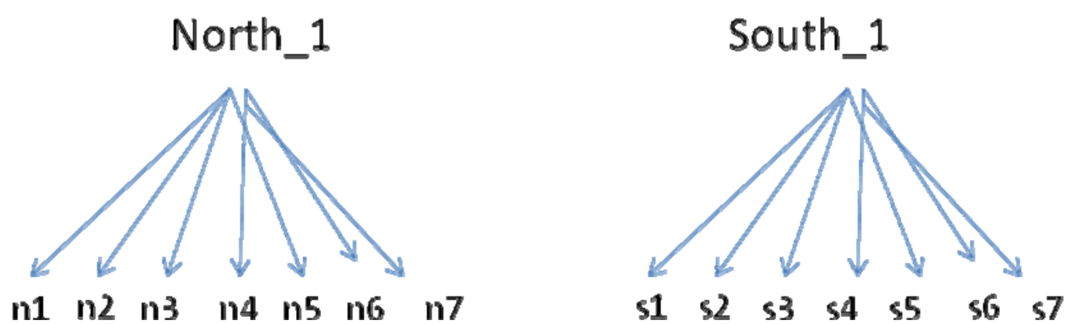

Figure 46: River Search Communication Hierarchy.

- North_1 starts communicating with n1, n2, n3, n4, n5, n6, n7 from 1 second
- South_1 starts communicating with s1, s2, s3, s4, s5, s6, s7 from 1 second
- The communication is 2 way.

TRANSMISSION DATA

- Packet Inter Arrival Time (Seconds) – Exponential (1)
- Packet Size in Bits – Exponential (1024)
- Altitude of Nodes – 1 meter

- Data Rate – 11Mbps
- Transmit Power – 0.005 w
- Packet Reception Power Threshold – -95
- Wireless LAN Physical Characteristics – Direct Sequence
- AP Beacon Interval – 0.02 sec
- Frequency – 700 MHz, 900 MHz, 2.4 GHz

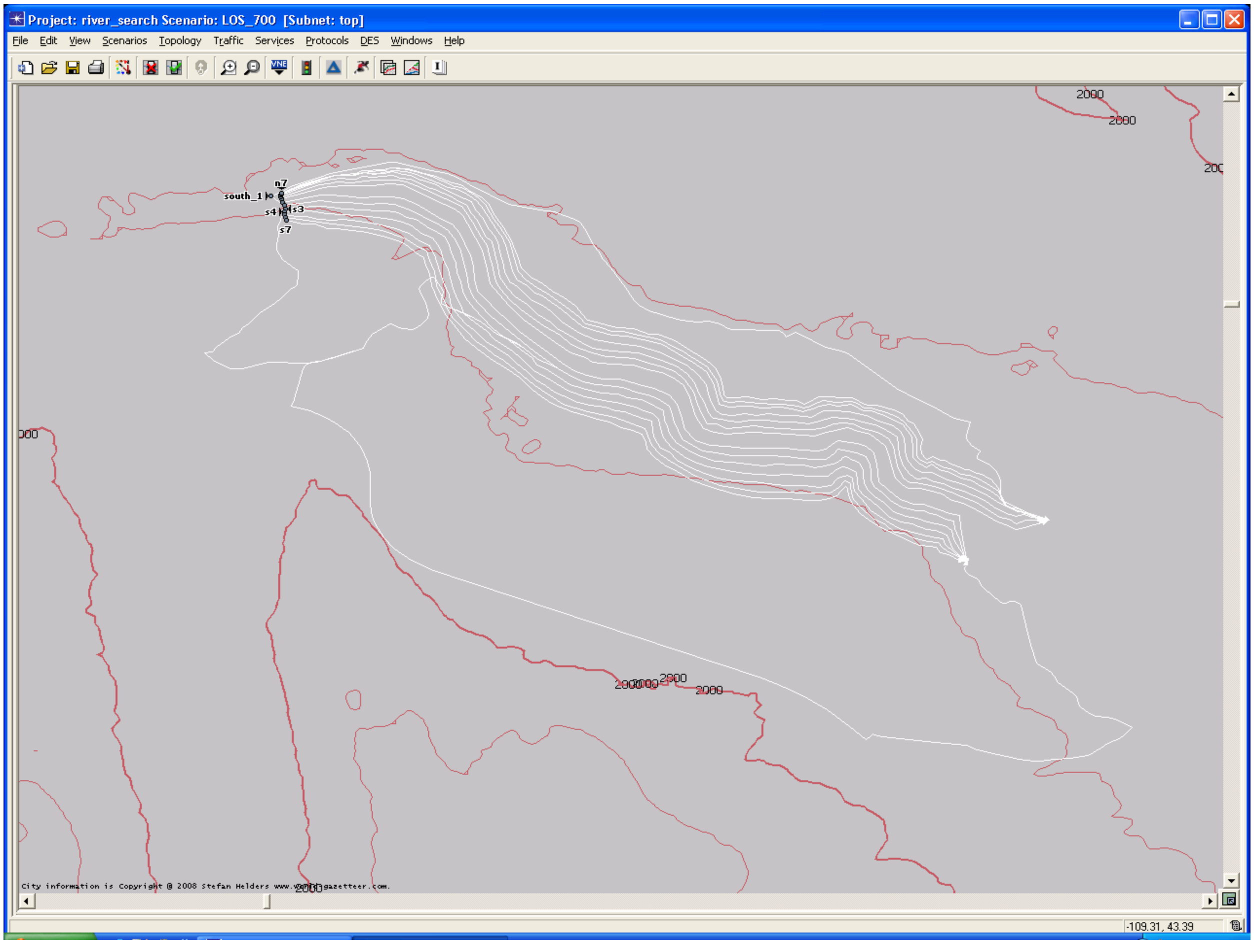

Figure 47: River Search Scenario Terrain.

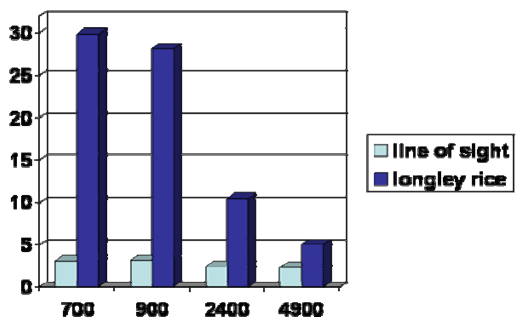

Figure 48: River Search - Percent Received Traffic for Free Space v.s. Longley Rice

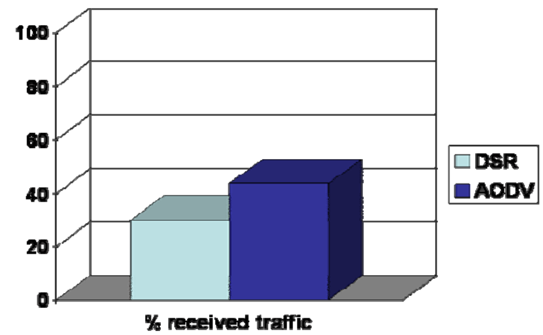

Figure 49: River Search - Percent Received Traffic at 700 MHz for DSR and AODV with Longley Rice

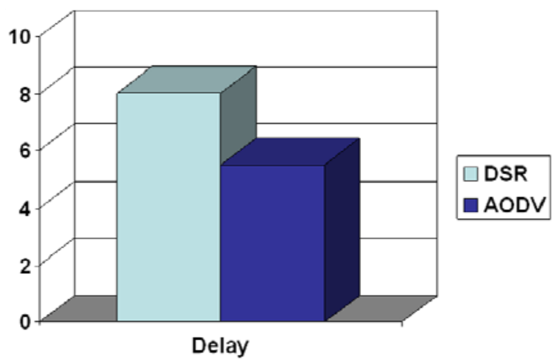

Figure 50: River Search - Delay at 700MHz for Longley Rice for DSR and AODV

9.3.2. Dam Breach Scenario

NUMBER OF NODES:

23 NODES: ns1, ns2, ns13, ns14, ns16, ns17, ns18, ns19, ns15, ew1, ew2, ew4, ew5, ew6, ew7, ew8, ew9, ew10, ew11, ew3, 120, Bn, bs

LENGTH OF SCENARIO

2 hrs 30 minutes

COMMUNICATION HIERARCHY

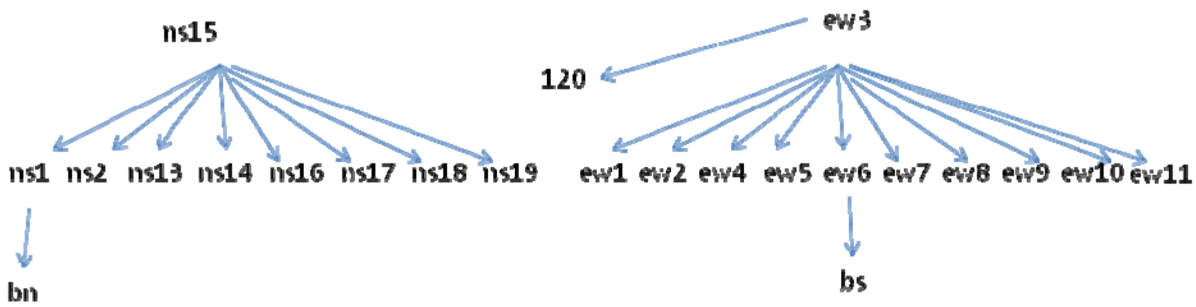

Figure 51: Dam Breach Scenario - Communication Hierarchy.

- ns1, ns2, ns13, ns14, ns16, ns17, ns18, ns19 starts communicating with ns15 from 1 second
- ew1, ew2, ew4, ew5, ew6, ew7, ew8, ew9, ew10, ew11 starts communicating with ew3 from 1 second
- bn starts communicating with ns1 from 1 second
- bs starts communicating with ew6 from 1 second
- 120 starts communicating with ew3 from 1 second

TRANSMISSION DATA

- Packet Inter Arrival Time (Seconds) – Exponential (0.5)
- Packet Size in Bits – Exponential (1024)
- Altitude Of Nodes – 1 meter
- Data Rate – 11Mbps
- Transmit Power – 0.005 w
- Packet Reception Power Threshold – -95
- Wireless LAN Physical Characteristics – Direct Sequence
- AP Beacon Interval – 0.02 sec
- Frequency – 700 MHz, 900 MHz, 2.4 GHz

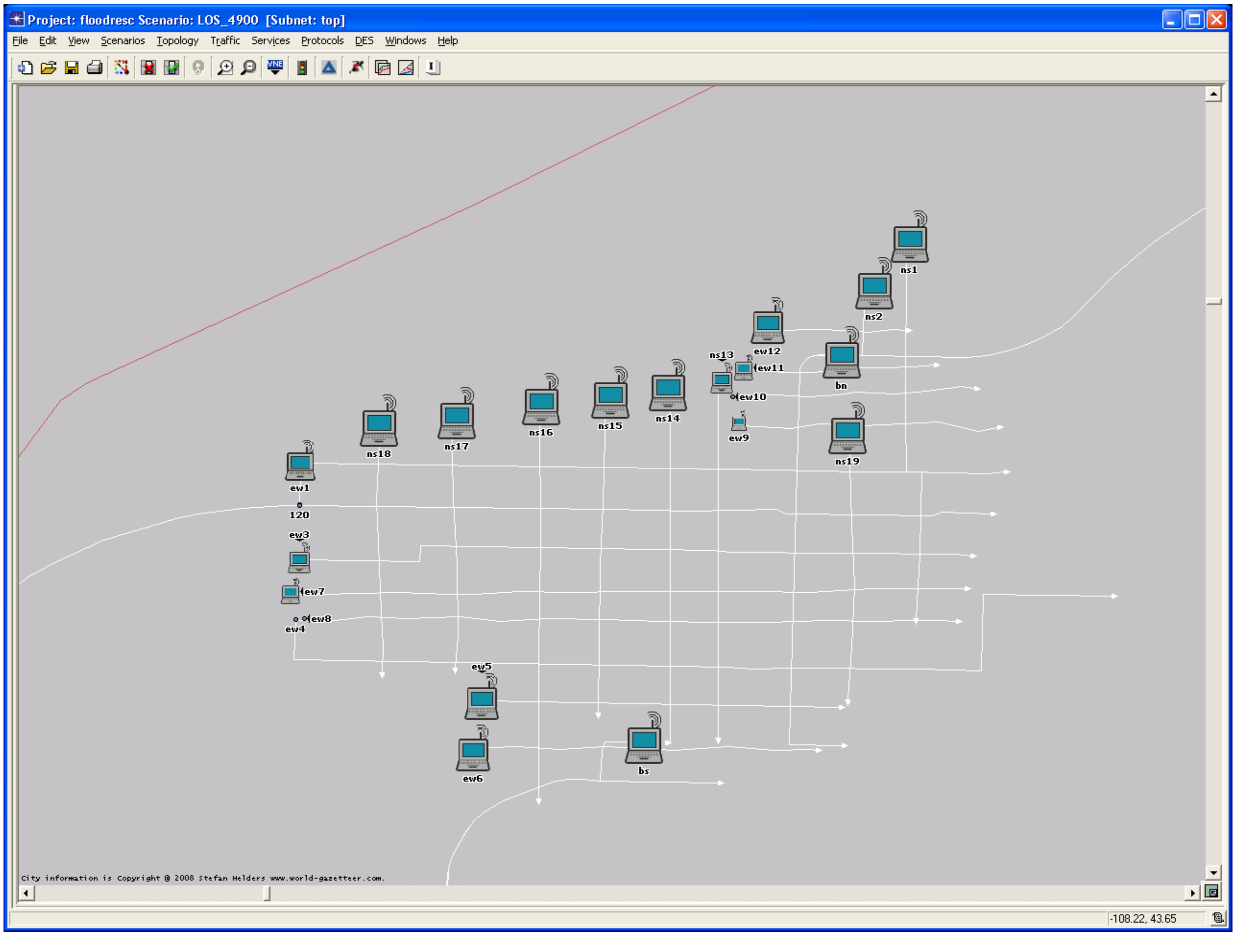

Figure 52: Dam Breach Scenario.

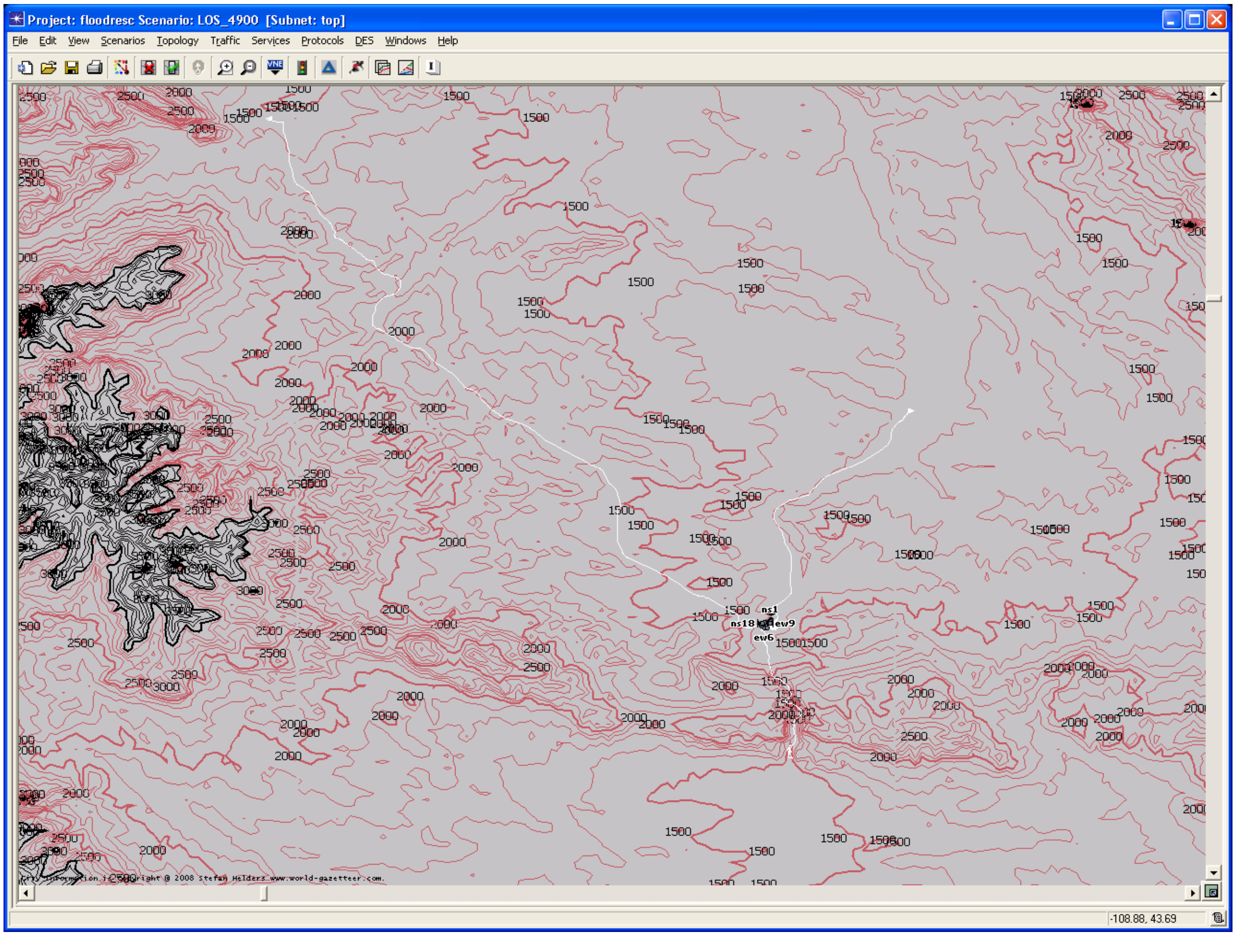

Figure 53: Dam Breach Scenario Surrounding Area.

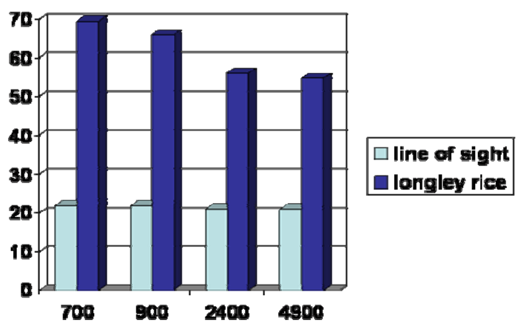

Figure 54: Dam Breach - Percent Received Traffic for Free Space vs. Longley Rice

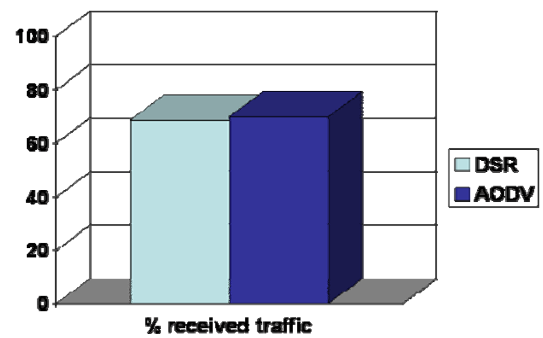

Figure 55: Dam Breach - Percent Received Traffic at 700 MHz for DSR and AODV with Longley Rice

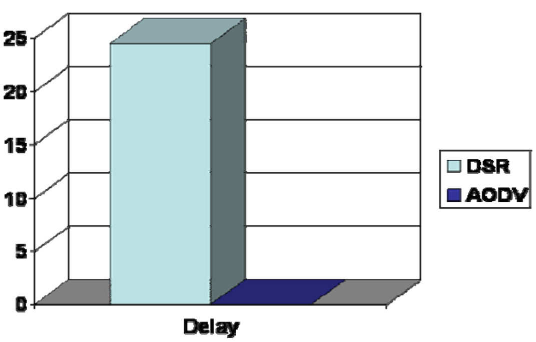

Figure 56: Dam Breach – Delay at 700 MHz for Longley Rice for DSR and AODV

9.3.3. Black Mountain Fire Scenario

NUMBER OF NODES:

15 NODES: SHERIFF 1, SHERIFF 2, FIRETRUCK 1, FIRETRUCK 2, FIRETRUCK 3, FIRETRUCK 4, FIREMAN11, FIREMAN12, FIREMAN21, FIREMAN22, FIREMAN31, FIREMAN32, FIREMAN41, FIREMAN42, FIREPUMPER

LENGTH OF SCENARIO

4 hrs 6 minutes

COMMUNICATION HIERARCHY

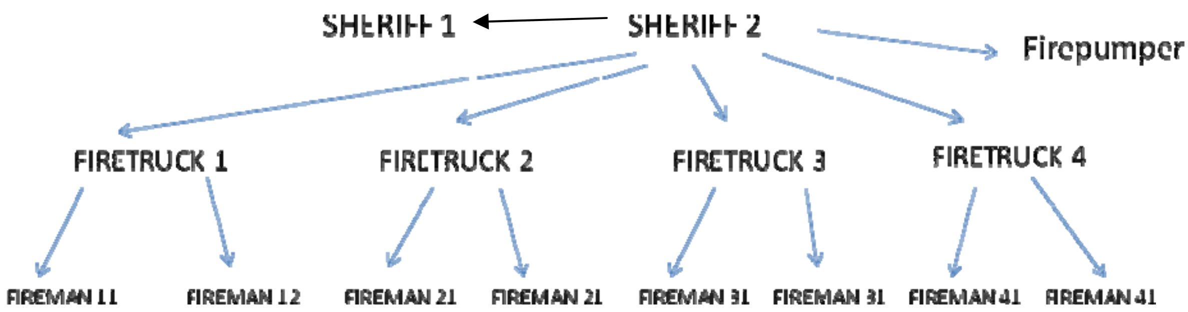

Figure 57: Black Mountain Communication Hierarchy.

- Sheriff 2 starts communication with fire trucks from 3600 seconds
- Fire trucks start communication with their firemen at 3900 seconds.
- Sheriff 2 starts communication with fire pumper from 3600 seconds
- Sheriff 2 starts communication with sheriff 1 from 3600 seconds
- The communication is two-way.

TRANSMISSION DATA

- Packet Inter Arrival Time (Seconds) – Poisson (1)
- Packet Size in Bits – Exponential (1024)
- Altitude of Nodes – 2 meters
- Data Rate – 11Mbps
- Transmit Power – 0.005 w
- Packet Reception Power Threshold – -95
- Wireless LAN Physical Characteristics – Direct Sequence
- AP Beacon Interval – 0.02 sec
- Frequency – 700 MHz, 900 MHz, 2.4 GHz

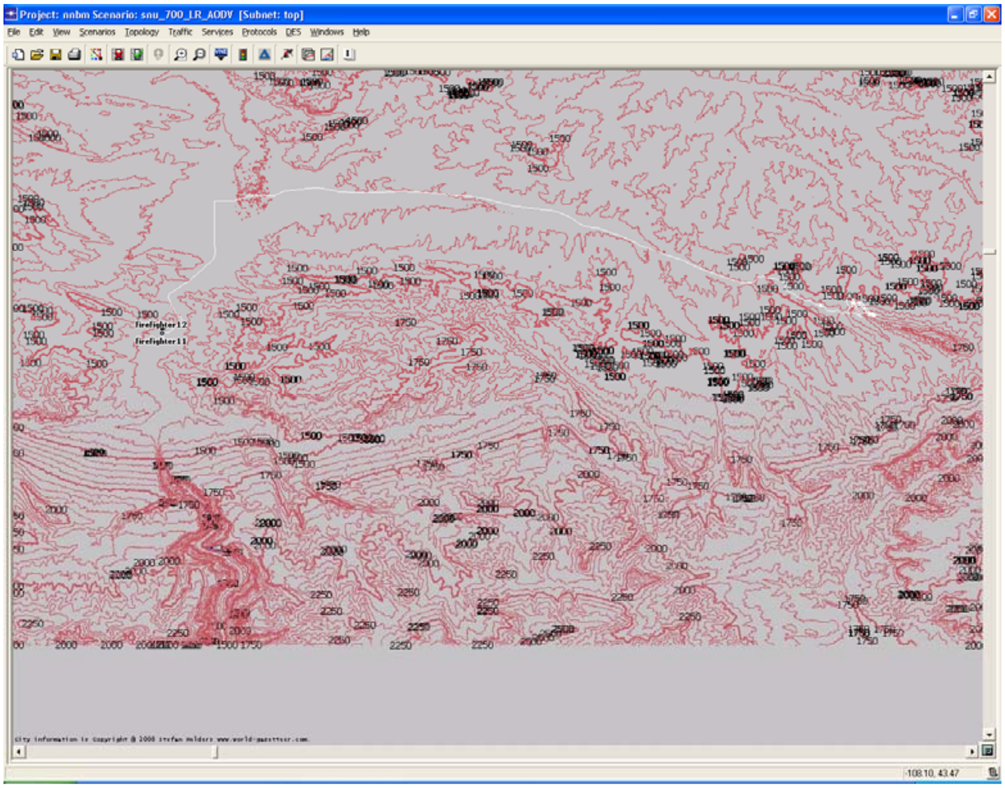

Figure 58: Black Mountain Scenario.

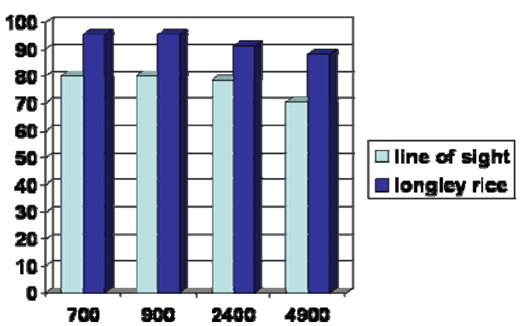

Figure 59: Black Mountain - Percent Received Traffic for Free Space vs. Longley Rice

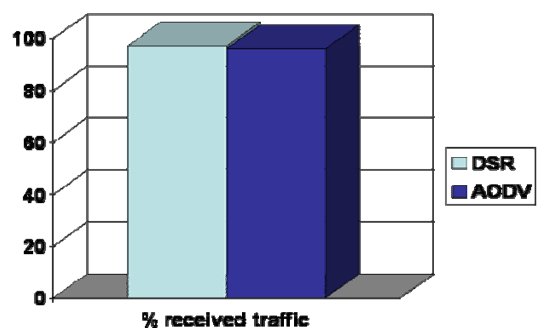

Figure 60: Black Mountain - Percent Received Traffic at 700 MHz for DSR and AODV with Longley Rice

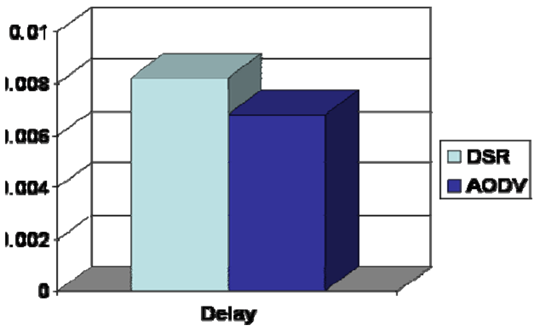

Figure 61: Black Mountain - Delay at 700 MHz for Longley Rice for DSR and AODV

9.3.4. HAZMAT Response Scenario

NUMBER OF NODES:

16 NODES: HN1, HNE2, HSE3, HW4, HW5, HWS6, HN, HS, HT1, HT2, HT3, HT4, HT5, HT6, HT7, HT8

LENGTH OF SCENARIO

three hours

COMMUNICATION HIERARCHY

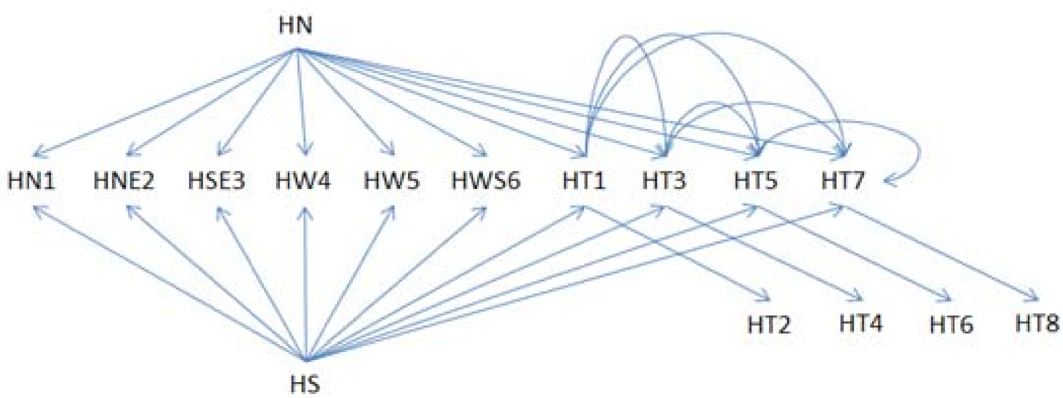

Figure 62: HAZMAT Communication Hierarchy.

COMMUNICATION TRAFFIC

- HN ---> HN1 ------> starting 6300 sec until 14400 sec(4 hrs)
- HN ---> HNE2 ------> 6300 sec
- HN ---> HSE3 ------> 6300 sec
- HN ---> HW4 ------> 6300 sec
- HN ---> HW5 ------> 6300 sec
- HN ---> HWS6 ------> 6300 sec
- HN ---> HT1 ------> 6300 sec
- HN ---> HT3 ------> 6300 sec
- HN ---> HT5 ------> 6300 sec
- HN ---> HT7 ------> 6300 sec
- HS ---> HN1 ------> 6300 sec
- HS---> HNE2 ------> 6300 sec
- HS---> HSE3 ------> 6300 sec
- HS---> HW4 ------> 6300 sec
- HS ---> HW5 ------> 6300 sec
- HS ---> HWS6 ------> 6300 sec
- HS ---> HT1 ------> 6300 sec
- HS ---> HT3 ------> 6300 sec
- HS ---> HT5 ------> 6300 sec
- HS ---> HT7 ------> 6300 sec
- HT1-------> HT2 --------->starting 900sec until 14400 sec(4 hrs)
- HT1-------> HT3 --------->900sec
- HT1-------> HT5 --------->900sec
- HT1-------> HT7 --------->900sec
- HT3-------> HT1 --------->900sec
- HT3-------> HT4 --------->900sec
- HT3-------> HT5 --------->900sec
- HT3-------> HT7 --------->900sec
- HT5-------> HT1 --------->900sec
- HT5-------> HT3 --------->900sec
- HT5-------> HT6 --------->900sec
- HT5-------> HT7 --------->900sec
- HT7-------> HT1 --------->900sec
- HT7-------> HT3 --------->900sec
- HT7-------> HT5 --------->900sec
- HT7-------> HT8 --------->900sec
- The communication is 2 way.

TRANSMISSION DATA

- Packet Inter Arrival Time (Seconds) – Exponential (1)
- Packet Size in Bits – Exponential (1024)
- Altitude of Nodes – 0.5 meters
- Data Rate – 11Mbps
- Transmit Power – 0.005 w
- Packet Reception Power Threshold – -95
- Wireless LAN Physical Characteristics – Direct Sequence
- AP Beacon Interval – 0.02 sec
- Frequency – 700 MHz, 900 MHz, 2.4 GHz

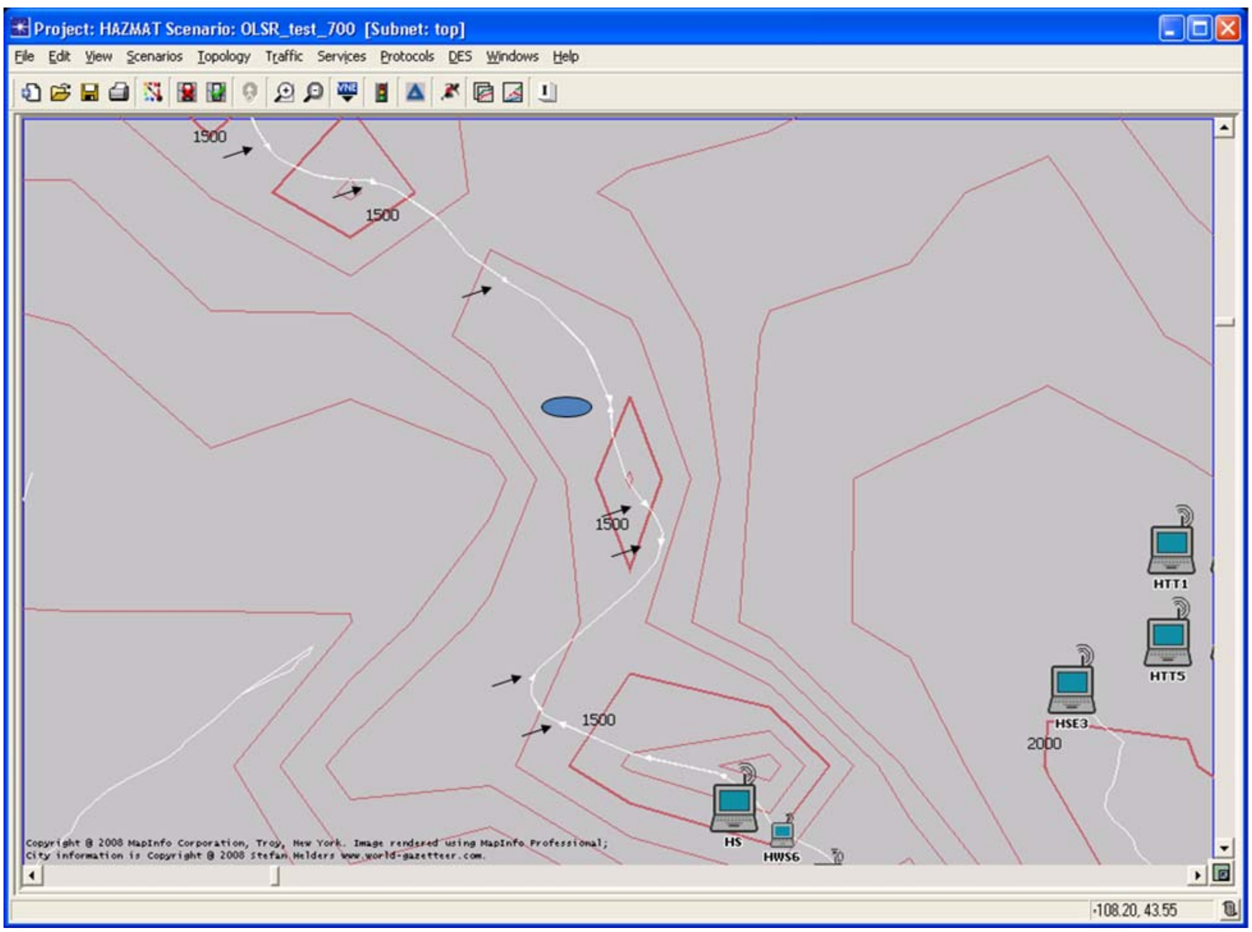

Figure 63: HAZMAT Response Scenario.

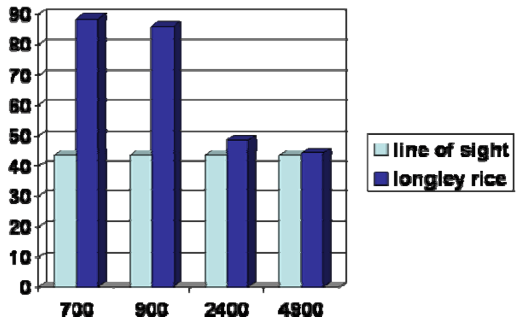

Figure 64: HAZMAT Response - Percent Received Traffic for Free Space LOS vs. Longley Rice

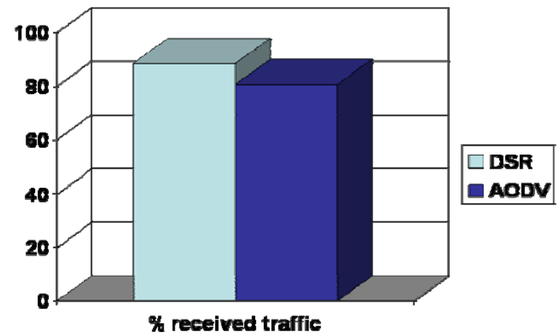

Figure 65: HAZMAT Response - Percent Received Traffic at 700 MHz for DSR and AODV with Longley Rice

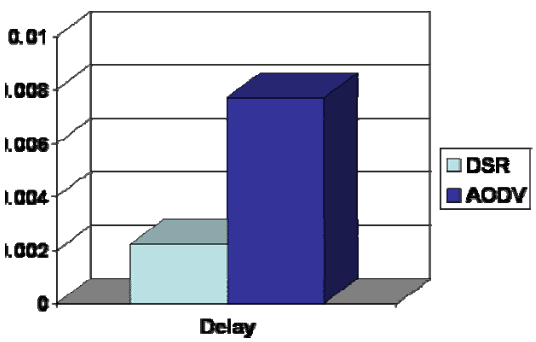

Figure 66: HAZMAT Response - Delay at 700 MHz for Longley Rice for DSR and AODV

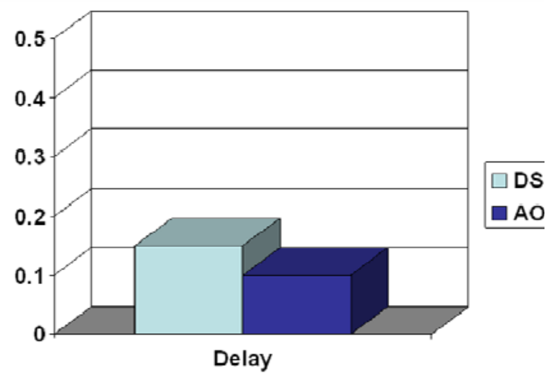

Figure 67: HAZMAT Response - Delay at 700MHz for LOS for DSR and AODV

9.4. Discussion of Baseline Results

Frequency dependence

Results for all the scenarios show greater throughput using lower frequencies. The trend is more pronounced where Longley-Rice propagation is assumed. For LOS, the throughput is less sensitive to frequency, provided the nodes stay within transmission range. This is noted in the river search, HAZMAT and dam breach scenarios, where the searchers are typically close together, and the throughput for LOS is almost independent of frequency. In the Black Mountain fire case, the firefighters are distributed over a large area, and the throughput at the lower frequencies is higher.

Propagation model dependence

The effect of using a realistic propagation model that takes terrain effects into account is pronounced, particularly at lower frequencies. The Longley-Rice model includes terrain effects, diffraction and surface conditions, as well as frequency. The LOS model takes terrain effects into account by calculating blockage, but does not include diffraction and other effects. Hence the Longley-Rice calculations allow for non-LOS propagation. The comparison between LOS and Longley-Rice shows that in every scenario, and at every frequency, the use of Longley-Rice yields significant increases in throughput, ranging up to a factor of three at 700MHz n the dam breach scenario. The increased throughput due to non-LOS propagation becomes less as the frequency increases, as diffraction effects are frequency-dependent. In the HAZMAT scenario, the throughput based on Longley-Rice propagation drops from 88 percent at 700MHz to 42 percent at 4.9GHz. The throughput based on LOS propagation is 41 percent at all frequencies for this scenario.

Routing protocol dependence

Simulations were run at 700MHz using Longley-Rice propagation to compare throughput and delay based on DSR and AODV routing. Both are reactive protocols, but DSR can be more effective in finding and maintaining end-to-end paths. The results for all scenarios show that DSR yields better performance, measured in terms of higher throughputs and lower end-to-end delays. The throughput differences are typically a few percent, but the delay differences are much more pronounced. In the HAZMAT scenario, for example, DSR yields an average 2ms delay, while AODV yields an average 8ms delay. The increased delay with AODV may be due to the protocol caching data at intermediate nodes when routes are broken, and then delivering the data later when the a new route is discovered. DSR, in contrast, flushes data from intermediate nodes when a new route cannot be found after a time-out interval.

9.4.1. QASR Simulation Results

In this section we present results of OPNET-based simulations where we have used the four scenarios described previously. For each set of simulations, we compare the performance of QASR with other routing reactive routing protocols, DSR and AODV. The simulations were carried out at 700MHz, 2.4GHz and 4.9GHz and the Longley-Rice propagation model was employed. The total traffic demand was varied from 600kb/s to 2700kb/s to explore the behavior of the protocols based on six metrics: throughput, delay, jitter, overhead, packet delivery ratio and QoS satisfaction ratio. See Figure 68 through Figure 73.

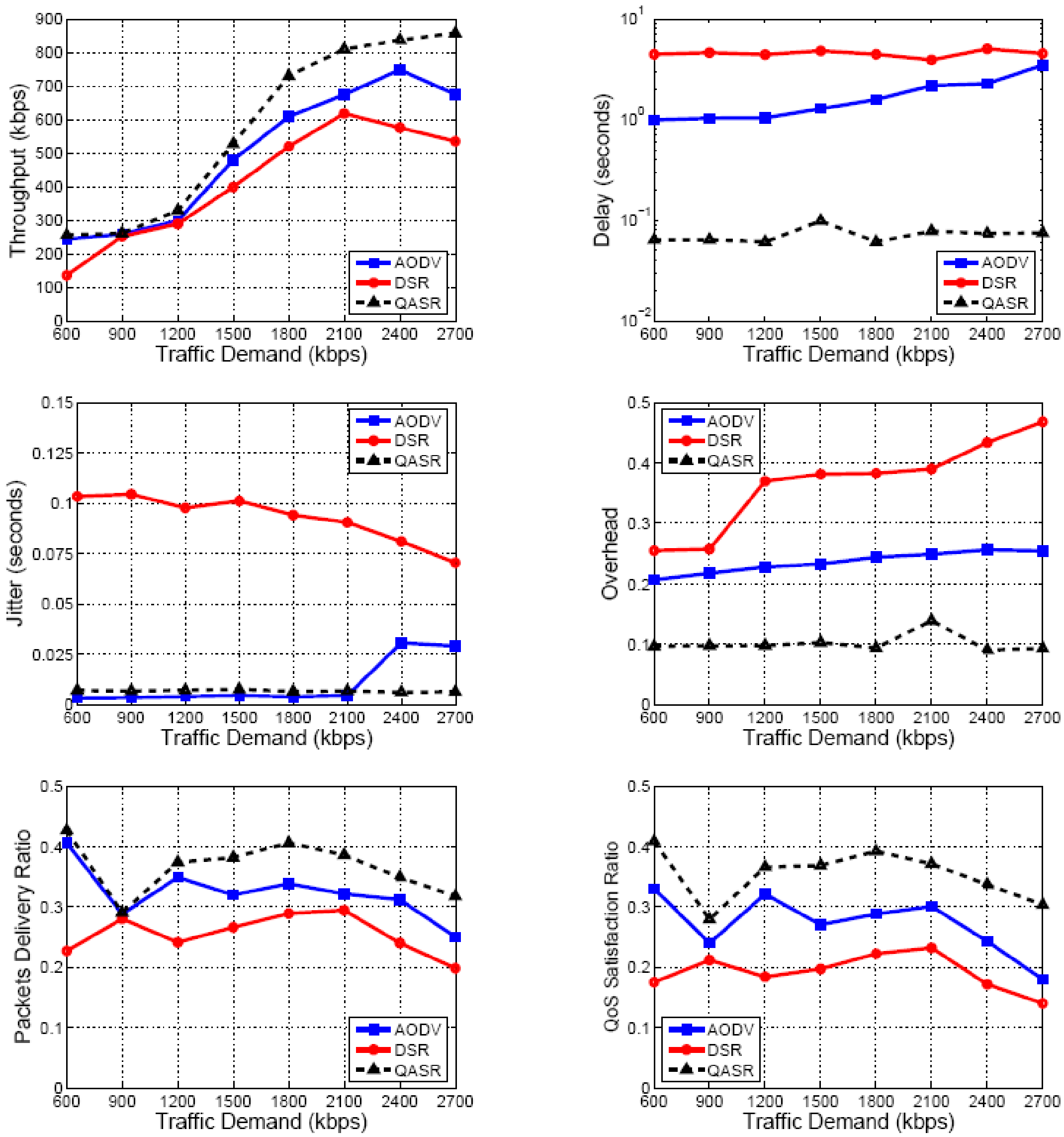

Figure 68: QASR Simulation Results – Dam Breach Scenario (2.4 GHz).

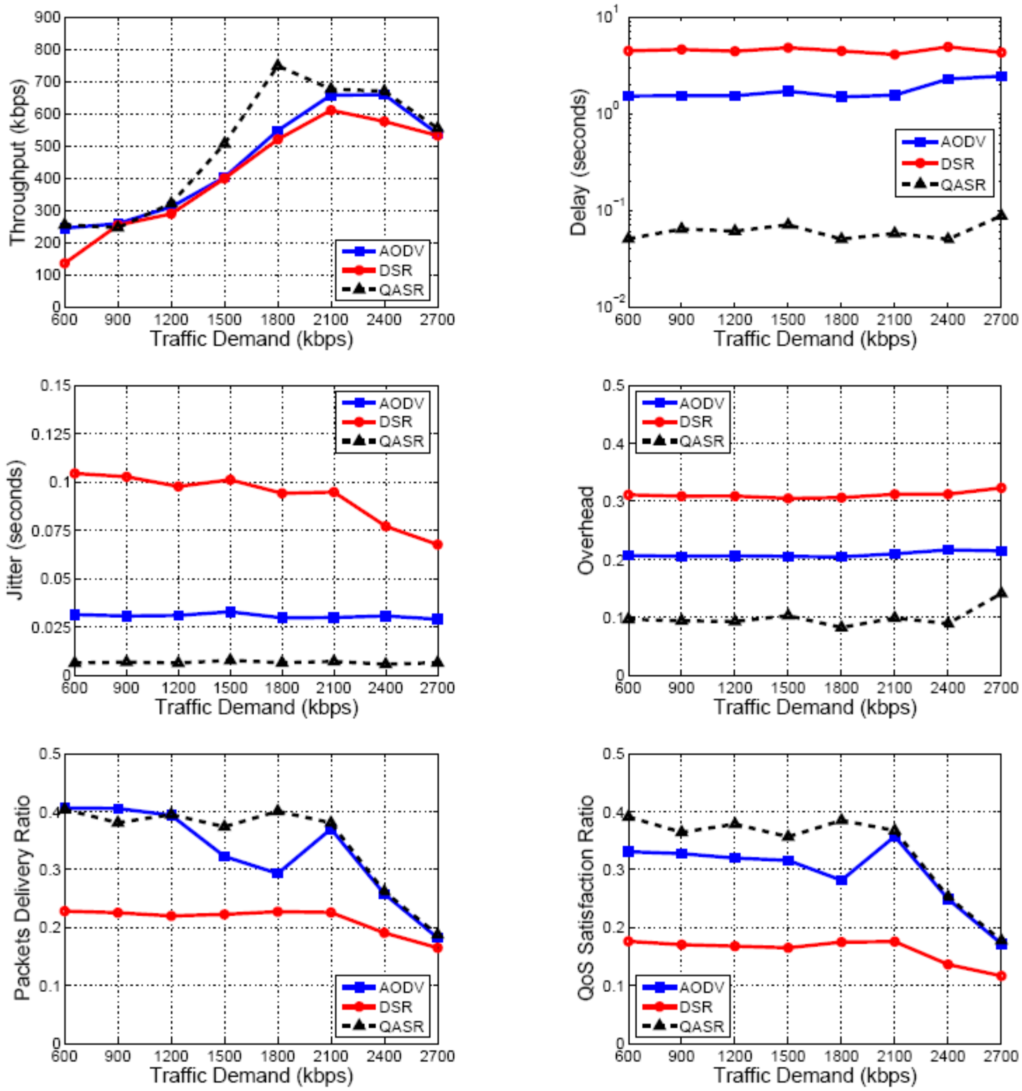

Figure 69: QASR Simulation Results – Dam Breach Scenario (4.9 GHz).

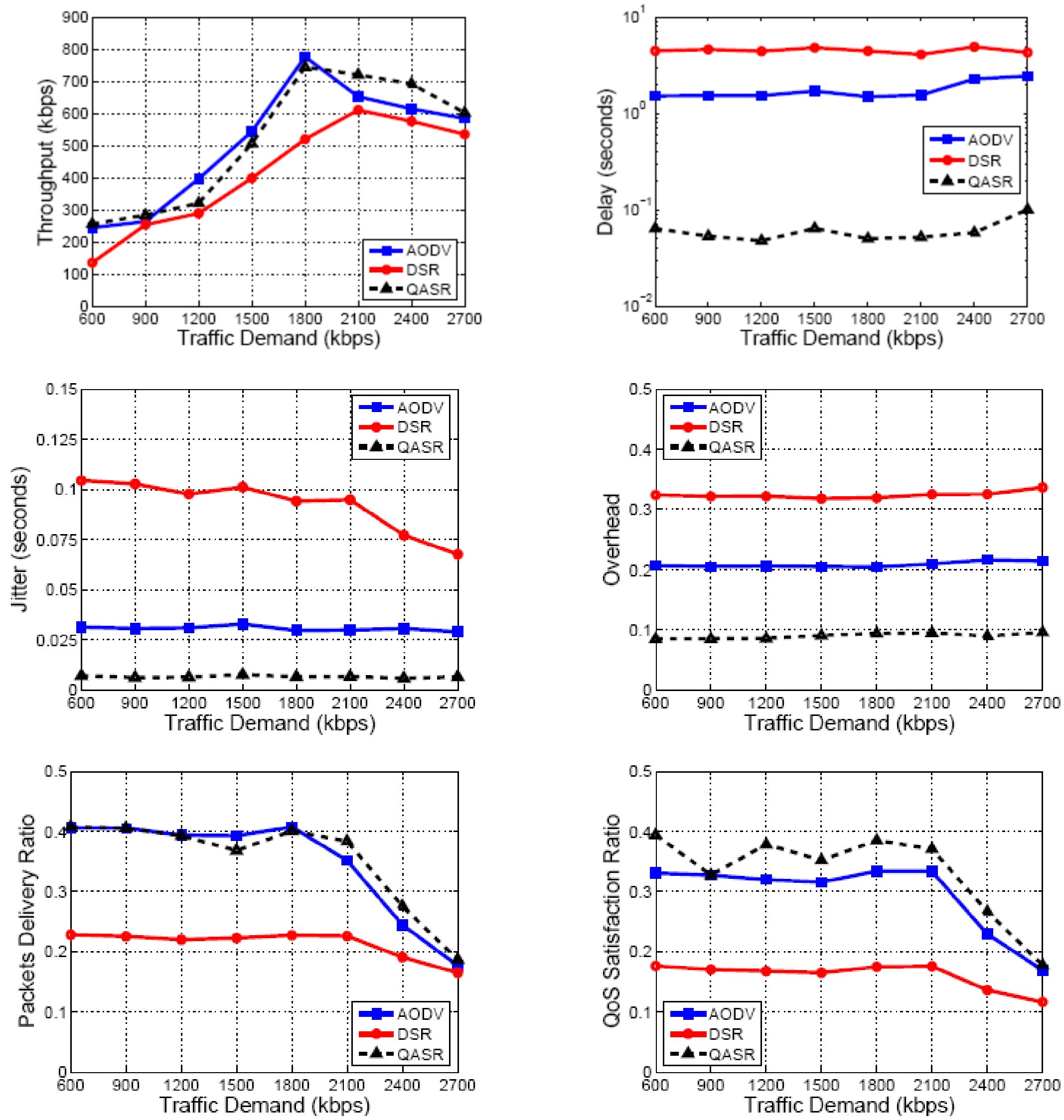

Figure 70: QASR Simulation Results – Dam Breach Scenario (700 MHz).

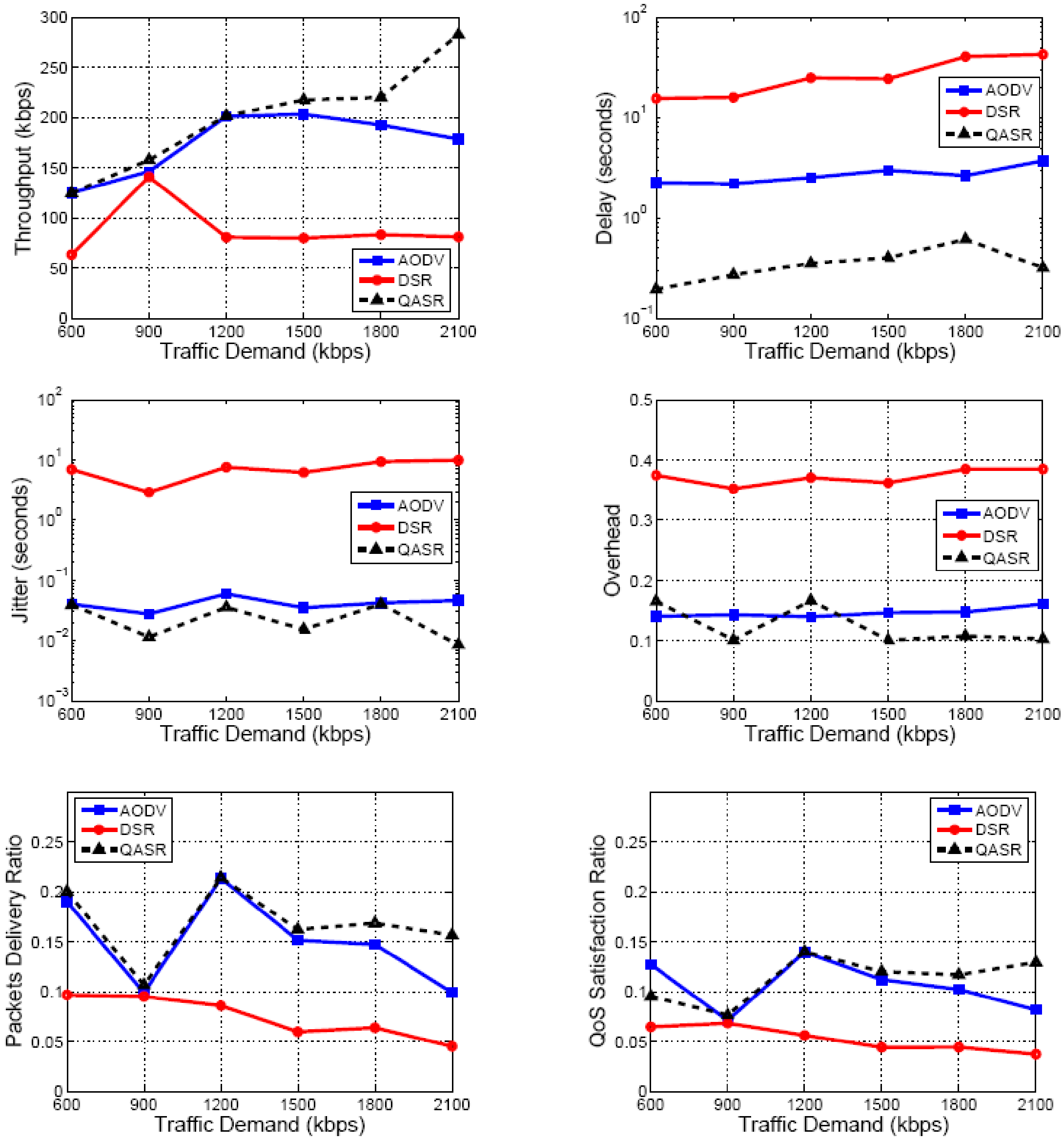

Figure 71: QASR Simulation Results – River Search Scenario.

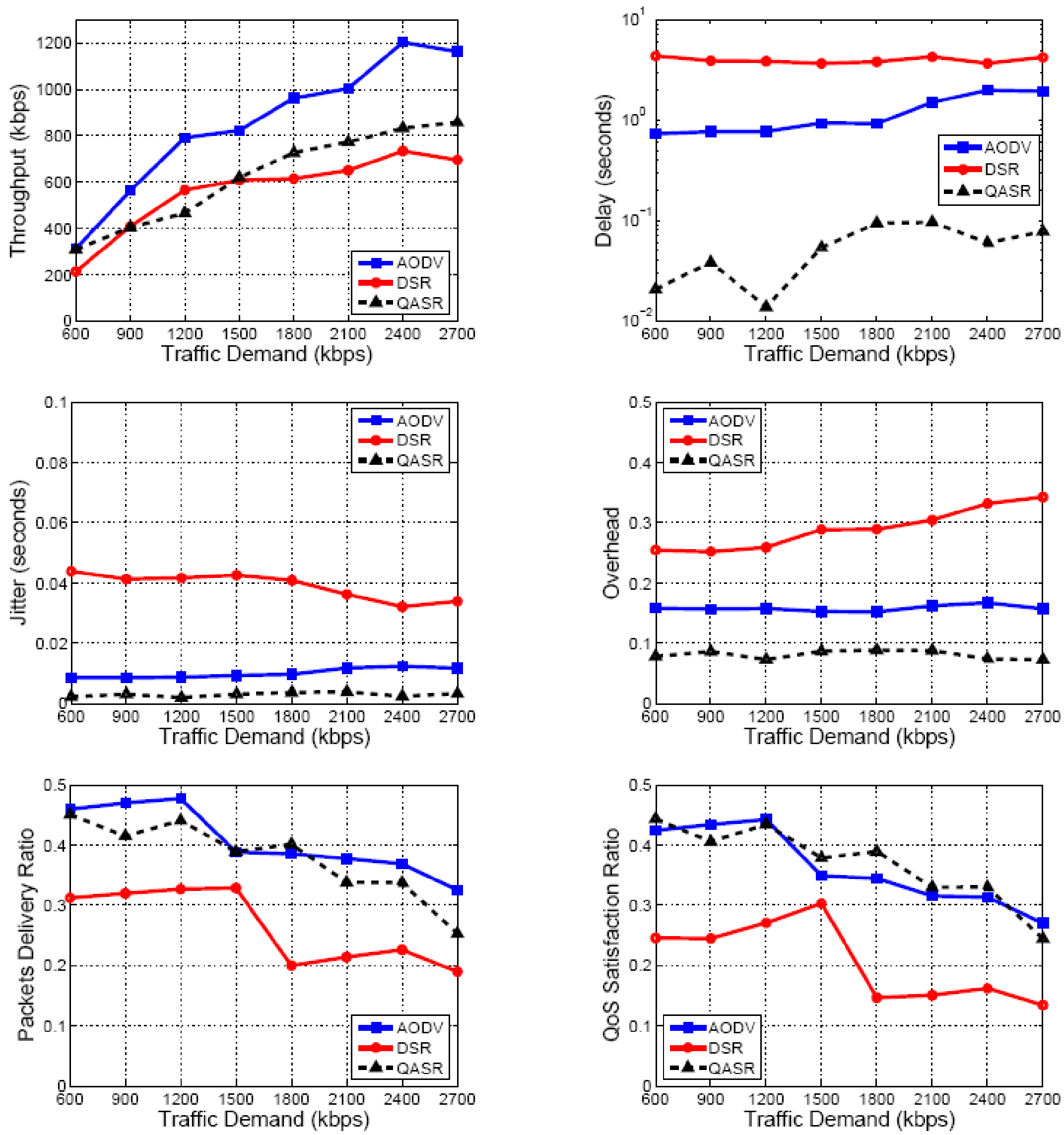

Figure 72: QASR Simulation Results – Black Mountain Fire Scenario.

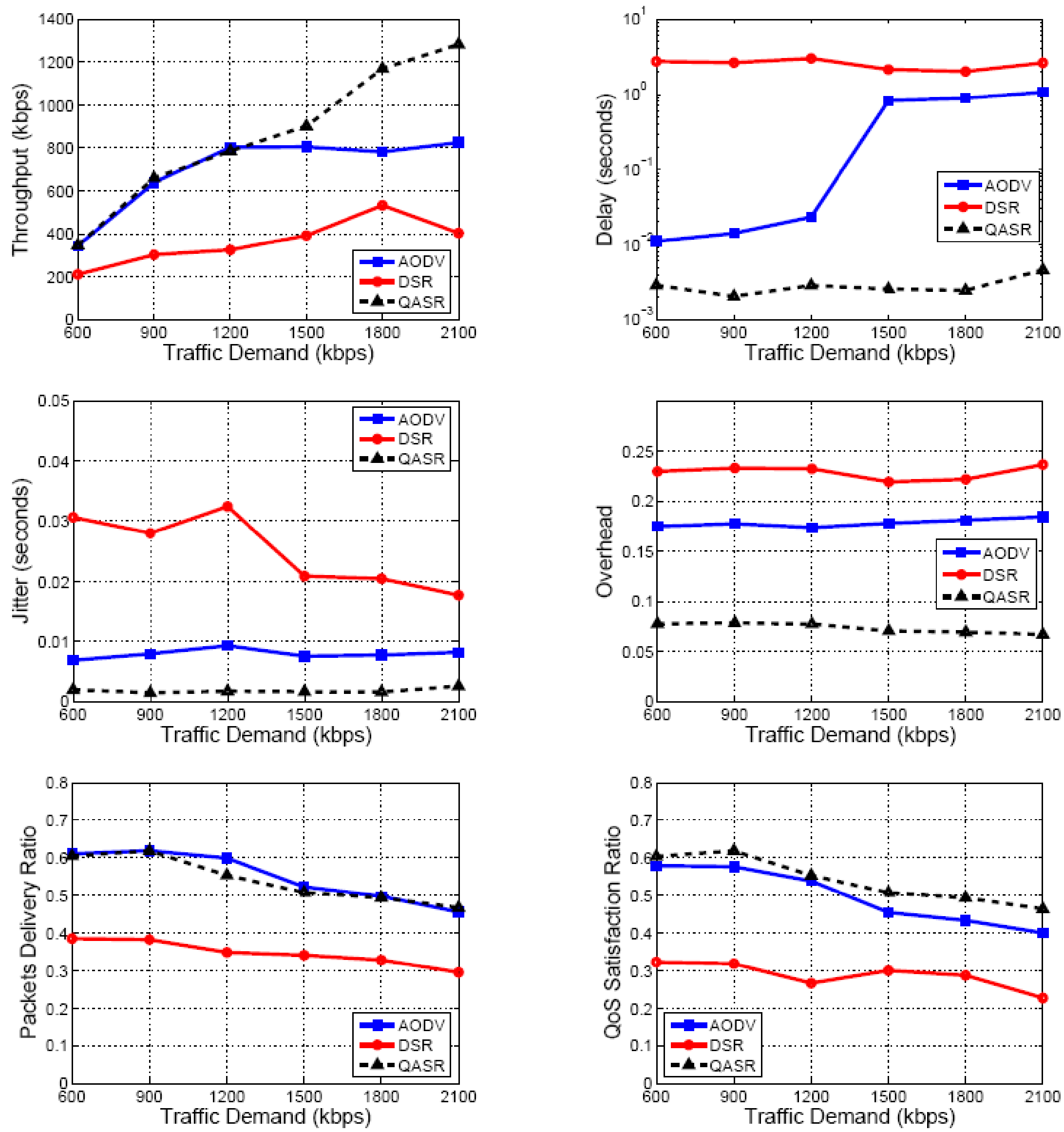

Figure 73: QASR Simulation Results – HAZMAT Response Scenario.

9.5. Analysis of the Simulation Results

Throughput, delay, jitter, packet delivery ratio, QoS satisfaction ratio and overhead are used as metrics for performance evaluation in the simulation, based on the two scenarios described in the last section. The throughput is the sum of sizes of all data packets successfully delivered from each flow's source node to its destination node. The delay is the average end-to-end delay of the data packets that are successfully delivered. The jitter is the average difference of the end-to-end delay of successive packets that are successfully delivered in a particular flow. The packet delivery ratio is the ratio between the number of data packets that are successfully delivered and the number of data packets generated in the application layer. The QoS satisfaction ratio is equal to the number of data packets that arrived within the delay and jitter tolerances over the total number of data packets successfully delivered. The overhead is the ratio between the sizes of control packets transmitted for routing-protocol-specific operations, such as route discovery, route maintenance and information exchange, and the sizes of all the control and data packets. The simulation results corresponding to scenarios are presented above in Figure 68 through Figure 73. From these figures, we make a number of observations.

In all scenarios, QASR performs significantly better than DSR and AODV in terms of all the metrics. The standard routing protocols always choose the shortest paths for routing without considering the bandwidth availability, traffic load status and mobility. Therefore, congestion is more likely to occur at the intermediate nodes and more retransmissions are needed for successful delivery of a packet, which will lead to poorer throughput, longer delay and larger overhead. On average, QASR outperforms DSR and AODV in terms of throughput by 65.7 percent and 4.39 percent, respectively. Moreover, the average delay given by DSR is 75 times greater than that given by QASR and the average jitter given by DSR is 233 times greater than that given by QASR. Note that the end-to-end delay and jitter are presented using a logarithm scale in the figures due to the large differences. The packet delivery ratios given by all the protocols are consistent with the end-to-end throughput. In terms of QoS satisfaction ratio, QASR offers 145.4 percent improvement over DSR and 27.8 percent improvement over AODV, on average, because of its ability to estimate available bandwidth and delay. Note that the estimation algorithms can certainly improve QoS but cannot provide a 100 percent guarantee (i.e., achieve a QoS satisfaction ratio of 100 percent) since the estimation may not be accurate and, more importantly, the estimation is made at the route discovery but the available bandwidth and delay may change during the actual data transmission in a highly dynamic MANET. In addition, compared to DSR and AODV, QASR reduces the average overhead from 31.8 percent and 18.2 percent to 11.8 percent respectively.

The routing protocols perform quite differently in different scenarios. In the river search scenario, they all perform very poorly due to intermittent connectivity among mobile nodes. In a poorly connected network, link breakage happens frequently. In this case, a large number of Route ERRor (RERR) messages will be generated to notify of failures, new RREQ and RREP messages need to be generated for rediscovering the routes, and more data packets need to be retransmitted multiple times to guarantee successful delivery. From the figures, we can see that QASR and AODV perform better than DSR but still suffer from poor throughput, long delay and large overhead. In the dam breach scenario where the network is connected most of time, the network performance is significantly improved no matter which protocol is used for routing.

The simulation results for the scenarios indicate several marked differences that can be attributed to the underlying connectivity characteristics and their effects on the behavior of the different protocols. In the river search scenario, the throughput does not tend to increase with traffic demand as might be expected, as the intermittent connectivity limits the overall packet delivery. In the dam breach scenario, where the network is more fully connected, the throughput increases with the traffic demand as expected, and all three protocols eventually reach a saturation level.

Simulation runs were also conducted to study the protocol behaviors on other spectrum bands including the ISM band at 2.4GHz (since most of previous research on ad-hoc routing focuses on this spectrum band) and the recently allocated public safety communication band at 700MHz. The selection of a lower operating frequency can provide either longer transmission range or increased link margin, which can translate into more alternative paths between a pair of source and destination nodes and a better link capacity with the use of adaptive modulation techniques. Moreover, when the terrain obstructs the LOS between nodes the use of lower frequencies is also favored, as frequency-dependent diffraction effects will enable NLOS communications. However, a larger transmission range will cause stronger interference and more collisions, which eventually will counteract the gain obtained by transmitting at a lower frequency. Therefore, we find out that the performance (throughput, delay, etc.) given by the routing protocols at the 700MHz and 2.4GHz bands are roughly the same as that at the 4.9GHz band. The QASR protocol still consistently outperforms AODV and DSR in terms of all the metrics.

9.6. Conclusions

In this report, by extending the functionalities of DSR, we designed a new ad-hoc routing protocol, QASR, to meet the QoS requirements of public safety communications. Extensive simulations were then conducted to evaluate the performance of QASR, DSR and AODV based on real, rural public safety scenarios including the river search scenario, HAZMAT scenario, Black Mountain fire scenario and dam breach scenario. Simulation results showed that QASR performs significantly better than DSR and AODV in terms of various performance metrics including throughput, delay, jitter, packet delivery ratio, QoS satisfaction ratio and overhead. These results further indicate that ad hoc routing can be a viable approach to meeting public safety communications needs in rural areas. We note that enabling steps are required, including: the development of the QASR protocol specification, embodiment of the protocol in executable software that can be tested in an actual test-bed rather than by modeling and simulation, and public review and discussion of the protocol in standards organizations such as the IETF.

10. DEMONSTRATION DESIGN

10.1. Introduction

As part of the Ad Hoc Routing for Rural Public Safety project, a proof-of-concept demonstration of mesh technology will be given to public safety officials from Hot Springs County and the surrounding area in August 2008. The demonstration will show the features of mesh networks and make use of applications based on rural public safety needs to demonstrate a data network.

The demonstration will take place in the Wind River Canyon where the rim of the canyon is approximately one mile wide and the walls are 1,700 feet deep. The topography of the area is challenging and at present, no radio communication is possible from the canyon to the surrounding area in the selected location. A mesh radio system will be used to provide communication between four parking areas on U.S. Highway 20. Vehicles equipped with mesh units will move into the parking areas and connect to stationary roadside nodes that provide links where distance and/or the geography limit communication.

The demonstration will highlight the self-forming and self-healing capabilities of the network, which, due to the narrow canyon floor, will be a serial network. The network will cover approximately 1.5 miles with eight nodes. Five nodes will be placed in static locations and three nodes will be installed in vehicles. Data traffic will be transmitted over the network from rugged laptop computers. Data types will include video, images, weather, and vehicle global positioning system (GPS) location data.

10.2. Radio Equipment Selection

Several forms of mesh product were evaluated for use in the proof-of-concept demonstration. Each had strengths but ultimately a rugged, self-contained mesh radio was chosen: the WTI MeshBox.

10.2.1. Microsoft Mesh Connectivity Layer

The Microsoft Mesh Connectivity Layer (MCL) is a software extension that creates a mesh framework. MCL is a true mesh and uses a modified version of DSR called Link Quality Source Routing (LQSR). As it is a software product, it must run on a computer with either Windows 2000 or Windows XP operating systems.

With this mesh implementation all nodes in the network would have to be actual computers and use the 802.11 radio built in to the computer for radio communication. While this approach has advantages in a desktop environment, it is problematic for a mobile vehicular-based system. Generally the networking cards inside laptops do not have external antenna ports so high-gain omni or directional antennas could not be added. Also, relay nodes (which could be left to sit on the side of the road for a full day of testing) would have to be a laptop or similar device, which generally has limited battery capacity, are not environmentally hardened and would have a high dollar value.

10.2.2. Wireless Distribution Service

Wireless Distribution Service (WDS) is a store-and-forward or relay method for connecting access points in an 802.11 wireless network. It is supported by many manufacturers as part of the software on wireless access points. Although WDS creates a transparent network capable of forwarding packets through many hops, it is not a true mesh protocol. It requires explicit setup of the network, and so it is not self-forming. WDS implementations are varied and can be vendor specific.

Early testing on wireless routers with WDS showed that a four-hop network would adequately carry video. However, WDS was found to be less stable than other alternatives. In some versions of WDS the ping command would not work consistently. A ping, which is normally used to show connectivity to a network device, would fail to a neighbor node even when pings would propagate through that node to devices several hops away.

10.2.3. MeshBox

Previous to the MANET project the researchers had explored the idea of creating an extendable and configurable networked radio device using open source software that was rugged enough to be used in a transportation environment. A project was proposed and awarded for a "Mobile Communications Briefcase for Rural Transportation Use," which included a system that became known as MeshBox. In the MeshBox, researchers used a consumer-grade wireless router running publically available, open source firmware to create a mesh radio and router (see Figure 74).

Figure 74: MeshBox Client and Gateway Nodes.

10.2.3.1. MeshBox Hardware

Because the researchers are focused on real-world transportation applications and field deployment, a rugged, waterproof enclosure was designed to allow use of the MeshBox in extreme conditions. External connectors are provided for dual antennas, Ethernet connections, and external or charge power. All connectors are water resistant and have caps for protection when not in use.

The enclosure (Figure 75) contains a NiMH battery pack that can provide approximately six hours of power. A custom circuit board allows battery charging, protection from over-discharge of the battery pack, and a battery capacity indicator.

The MeshBox system is made of two different types of units: client or relay nodes (orange box) and gateway nodes (yellow box). Both units are nearly identical except the gateway nodes have an external connection to the WAN port for connection to the Internet. Both units can provide a LAN connection to a single computer. In the system there are three gateway nodes and seven client nodes.

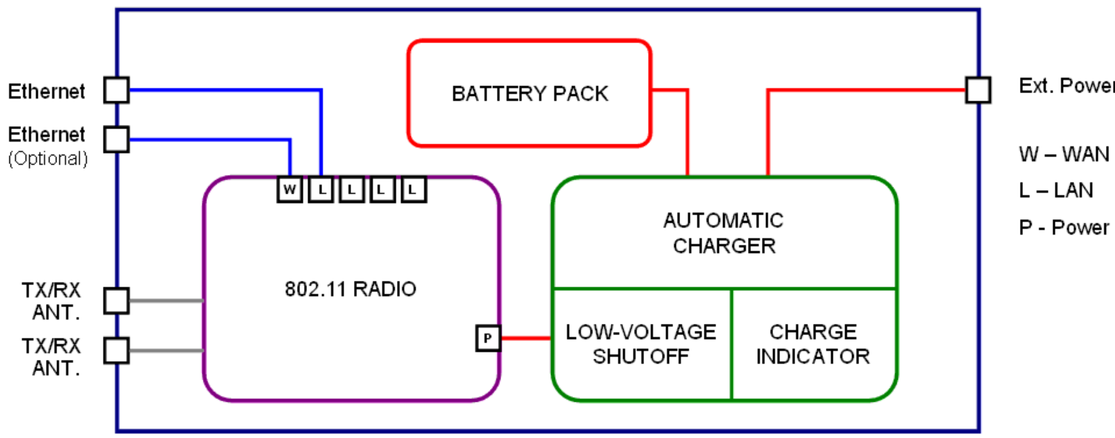

Figure 75: MeshBox Internal Components.

10.2.3.2. Freifunk - OpenWrt Embedded Linux Distribution

The WTI Systems Group has frequently used Linksys WRT54GL routers running various derivatives of a Linux-based router firmware called OpenWrt. OpenWrt (OpenWrt homepage: http://openwrt.org/) is an open source router firmware that can be installed on a wide range of hardware platforms.

The Freifunk (Freifunk homepage: http://www.freifunk.net/) firmware is a customized version of OpenWrt designed specifically for mesh networking. The firmware integrates the Optimized Link State Routing (OLSR) mesh routing protocol with easy-to-use tools including a graphical interface (see Figure 76). The Freifunk distribution of OpenWrt is used in the MeshBox system to provide mesh functionality.

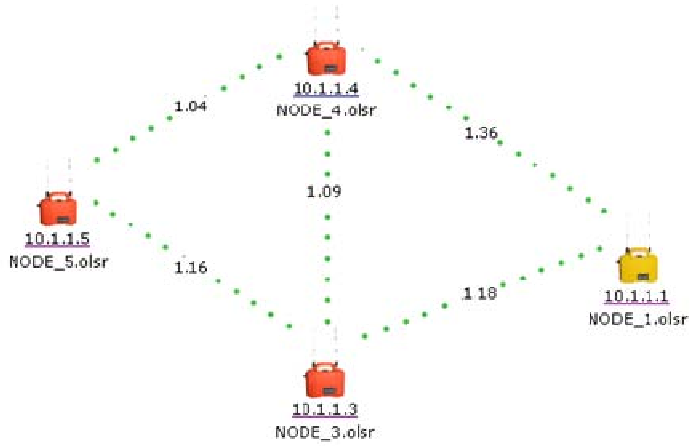

Figure 76: Freifunk Network Visualization Tool.

10.3. Site Selection

Prospective demonstration sites were chosen based on the following criteria:

- Allow or require the mesh network to exhibit self-forming and self-healing behavior
- Interesting terrain that does not allow radio or visual line of sight
- Roadway for mobile nodes (vehicles) to travel and set parking locations (pullouts)
- Space for creation of a connected network at distances not exceeding the selected mesh equipment
- Service coverage for connection to the Internet
- Parking space for the participants and observers
- A location that is easily accessible to all the observers
- Access to shelter in case of inclement weather

10.3.1. Black Mountain

Black Mountain is a four-mile-long ridgeline that rises up to 1,100 feet over the surrounding terrain in eastern Hot Springs County (Figure 77). The site was considered for the demonstration due to a fire that occurred at the southwest end of the mountain and traveled over the ridge to the northeast. During the fire, separate firefighting units lost connectivity with each other as they moved along the ridge. A Hot Springs County Sheriff's Deputy moved to the top of the ridge in harm's way to relay messages to the fire crews. Showing how a mesh network could relay data to disparate networks would give a powerful message to the local officers, many of whom took part in fighting this fire.

Figure 77: Prospective Demonstration Site, Black Mountain, WY.

The location was not chosen for the demonstration because of its remoteness, the fact that it was on private land, that it had no infrastructure to support the demonstration in inclement weather, and that the terrain was not interesting or challenging except for the ridge.

10.3.2. Wind River Canyon Site 1

Wind River Canyon site 1 is at the mouth of the Wind River Canyon just south of Thermopolis. This site has advantages including access to vehicle parking at the fishing access pullout, covered pavilions at the Canyon 1 pullout, and access to nearby pullouts for vehicle node parking at Canyon 2–4. A curve in the roadway shields view of the Canyon 4 pullout from the other pullouts (Figure 78).

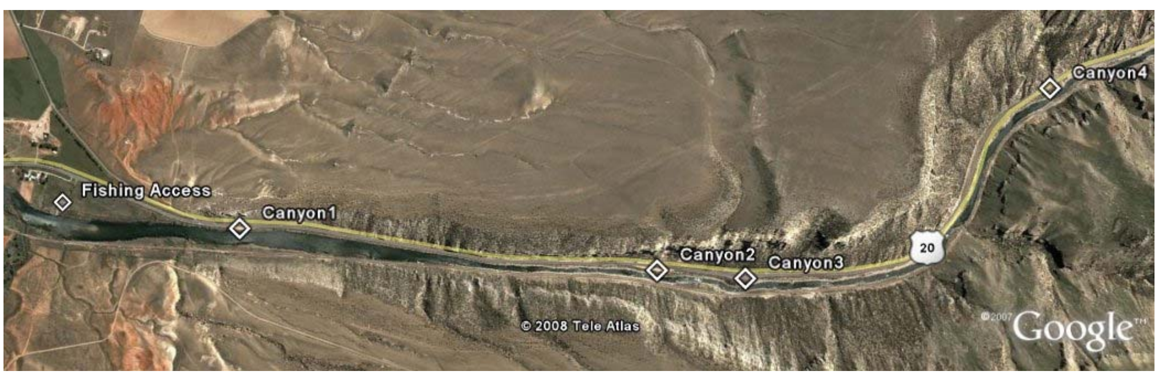

Figure 78: Prospective Demonstrations Site, Wind River Canyon, WY.

Although this site fit most of the requirements, it was not selected due to the distances required to connect the pullouts. This site requires a network length of over 2.5 miles. A network could not be built using omni-directional antennas to cover this distance. Directional antennas could have been used but the researchers felt that such a network would not demonstrate self-forming behavior.

10.3.3. Wind River Canyon Site 2

The second site in the canyon was suggested by Dave Larsen, a Hot Springs County Sherriff's Deputy. Like the site at the mouth of the canyon, this site also has access to vehicle parking, covered pavilions, and nearby pullouts for vehicle node parking. There is a picnic area with two covered pavilions that can serve as the demonstration area. The building close by provides facilities and a meeting area.

The picnic area is surrounded by trees. Views of the roadway are blocked and pullouts 2 and 3 are not visible or within line-of-sight of the demonstration area or pullout 1. The total distance from the demonstration area to pullout 3 is just over 1.2 miles and to pullout 4 it is just over 1.6 miles. Pullout 4 can be used for turning vehicles around during the demonstration.

The site provides very interesting and challenging terrain. The walls of the canyon are 2,000 feet deep in this area (Figure 79).

Figure 79: Selected Demonstration Site, Wind River Canyon, WY.

Because Wind River Canyon site 2 met all of the necessary criteria, it was chosen for the demonstration site. Dave Larsen requested use of the site from the property owner.

10.4. Public Safety Applications

To better show the public safety observers the benefits of mesh networks, several applications were selected that would be of interest to the audience. Before the project it was decided that database query, voice, video and images would be targeted for the demonstration. After the meeting with public safety officials and the assessment of rural public safety communication needs the list was modified. The public safety officials queried indicated that images, mapping, video and weather would be of use on a data network. These applications were chosen for the demonstration.

10.4.1. Mesh Application

In the process of designing the demonstration, WTI realized that there was a need for an application to demonstrate the network's capabilities. After some initial research it was determined that no application existed that would effectively demonstrate the capabilities of the MeshBox network and its use in incident response. The researchers began development of an internal application to showcase the capabilities of the mesh network, and demonstrate an application that first-responders would find valuable at the site of an incident.

The application was designed around the expected requirements of a first-responder. The application's network architecture is peer-to-peer, removing the need for a server. The application automatically seeks out and establishes communication with all other accessible nodes. Some of the application’s features include:

- Real-time automatic vehicle location (AVL) displayed atop satellite imagery overlaid with roads and road names
- Image sharing
- Image, map and whiteboard markup distribution
- Point weather forecast download and display (both text and graphic)
- Integration with Windows XP Tablet Edition, allowing first responders to use tablet PCs to easily markup imagery, maps and whiteboards using a stylus on the tablet’s display

The Tablet PC integration lends itself well to first responders, who need to convey their information with all other responders accurately and quickly.

The application was written in C# and extensively used the Microsoft Tablet PC 1.7 SDK, and uses the Apache 2 web server for large file distribution.

10.4.2. Video

During the demonstration planning phase it was determined that responders considered live video feeds to be valuable during incident response. The researchers tested video from a handheld Firewire video recorder encoded into a 32 kbps MPEG4 video stream using both Video LAN Client and Microsoft Video Encoder. Playback would be achieved with Video LAN Client. Integration of video into the Mesh Application was considered but rejected since there were very good applications that showed video.

10.5. Demonstration Internet Connectivity

10.5.1. Satellite Internet

Satellite Internet Service is available across all of Wyoming, and most rural location in the United States. WTI has a HughesNet system that can be moved out of the state of Montana. This service would provide adequate bandwidth for the demonstration and had LOS to a satellite at all the prospective locations. The selected location does have more tree cover and may require precise setup to choose a good location for the dish.

10.5.1.1. Coverage at Sites

It was verified that the satellite system would have a clear LOS from the location chosen for the ICP. The HughesNet system is commissioned for satellite G16. Using Google Earth a 3D line can be drawn from a selected site to the satellite in orbit. If the terrain interferes with the line then LOS is not present. Due to trees in the area and a necessary connection to Node 2, the best placement for the satellite dish is probably at Node 2 near the river’s edge (Figure 80).

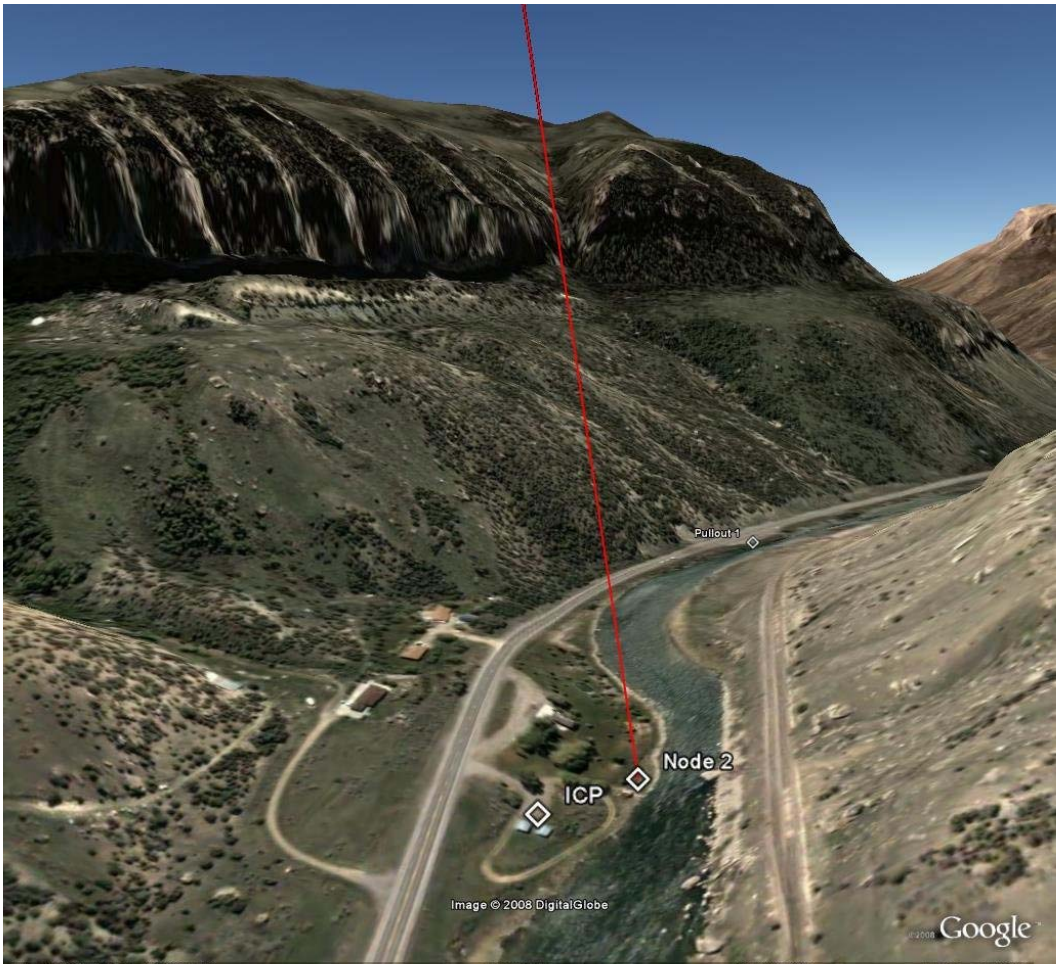

Figure 80: Satellite LOS at the ICP.

10.5.2. Cellular

Verizon provides cellular service to Hot Springs County. During the course of this project the cellular system around Thermopolis was upgraded from 1X-RTT service to EVDO-Rev A. Either service would provide adequate bandwidth for the demonstration.

10.5.2.1. Coverage at Sites

Early in the project the researchers surveyed the major roadways in Hot Springs County for cellular network signal strength. Using a Land Cellular CDMS modem, strength readings were recorded along with a GPS location. In Figure 81, the signal strength at the red triangle icons is in a range of zero to four where fifteen is required to create a network link. Because the signal strength at the chosen demonstration site is too weak to create network links, cellular service was eliminated from the demonstration.

Figure 81: Cellular Signal Strength Measured at the Demonstration Site.

10.6. Network Design

The design of the demonstration network was an attempt to reflect the network elements in the SOR. Figure 82 shows a draft design of the network before the equipment had been selected and tested. Pictured is a network that demonstrates all elements except a Personal Area Network (PAN) which can be simulated with a Wi-Fi capable digital camera and Bluetooth GPS units.

In the first iteration of the network design, several Incident Area Networks (IANs) were to be connected with 900 MHz radios acting as a Jurisdictional Area Network (JAN). The IAN was to be connected internally by a mesh or mesh-like system that would allow communication across several hops to the JAN gateway or the Internet connection.

This design was considered too complex and too risky but served as an illustration of a demonstration that closely matched the prospective reality portrayed in the SOR.

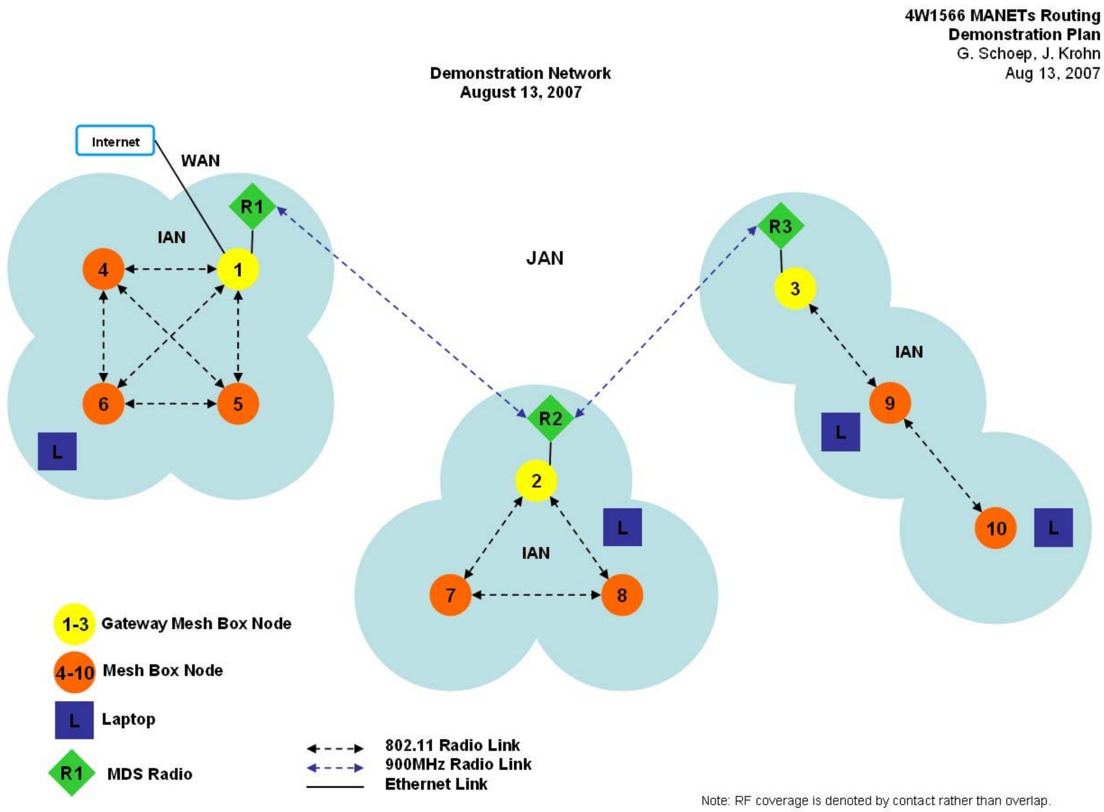

Figure 82: Prospective Network Design.

After use of 900 MHz radios as backhaul was discarded, a new network design emerged (Figure 83). It was possible to use the MeshBox system for the mesh network (IAN) and to use the Internet to simulate the JAN. Also, the Mesh Application required a location to be associated with a node. Rather then integrate a GPS into the MeshBox, it was decided to connect a GPS unit to a laptop and then attach the laptop to one MeshBox. Relay node locations are not required for the Mesh Application so they need no GPS or laptop to be connected.

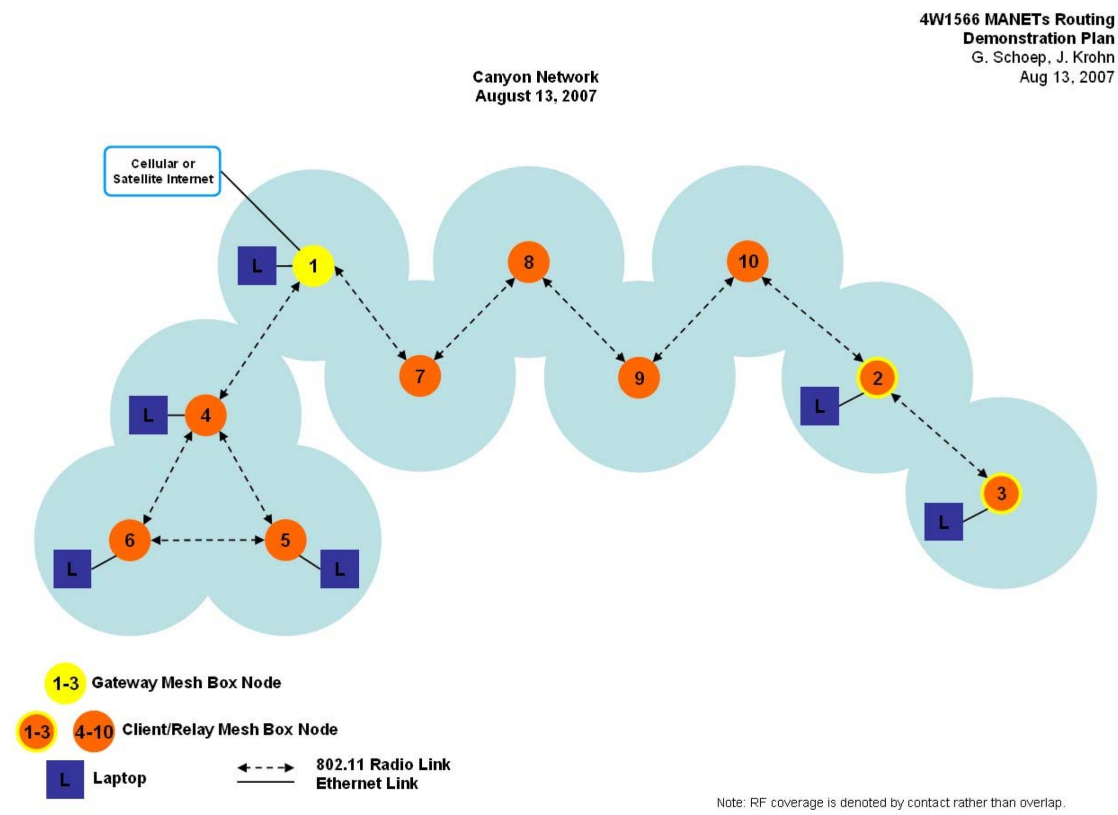

Figure 83: Demonstration Network Design.

10.6.1. Wireless Network Design Application

To create reliable radio links, which will fail when obstacles such as mountains, canyon walls, or vegetation block the line-of-sight path, engineers often use expensive software modeling packages. An alternative is to test all prospective radio links by deploying equipment in the field. Depending on terrain, this can be time-intensive and even impractical when many nodes must be placed in a network. Researchers concluded that a tool was needed to allow quick, effective pre-design of a working mesh network.

As part of the MeshBox System, a web-based design tool was developed that allows users to interactively place mesh nodes while visually verifying that the mesh network remains connected. The design tool uses high-resolution USGS elevation data to test radio propagation around each mesh node, and then plots the resulting coverage area in a Google Maps interface.

Users can easily move mesh nodes to view updated coverage areas and design a complete mesh network while ensuring that network fragmentation does not occur. Radio parameters such as frequency, receive antenna height, transmit antenna height, antenna gain, transmitter power out, and receive sensitivity can be adjusted for each node. Node templates can be saved for rapid parameter selection and new nodes can be created with the same settings of an existing node.

The Wireless Network Design Application was used to evaluate potential demonstration sites and give an indication of how many nodes were required to cover an area of roadway. The output of the application was viewed in Google Earth where terrain effects were verified (Figure 84).

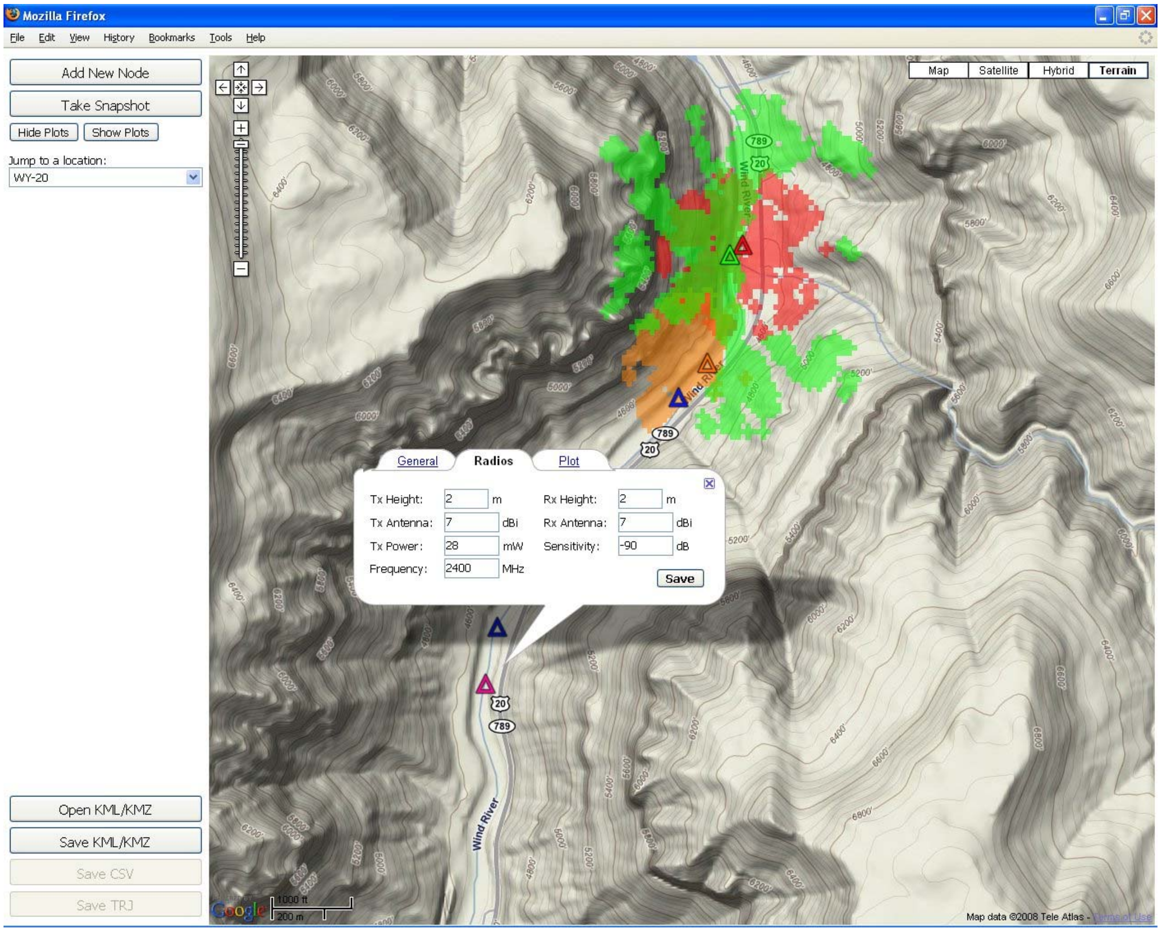

Figure 84: Wireless Network Design Application.

After selection of the demonstration site, the application was used to design a mesh network covering all the pullouts (Figure 85). For purposes of clarity, only the propagation studies for Nodes 1-4 are shown. The design was verified by testing on site.

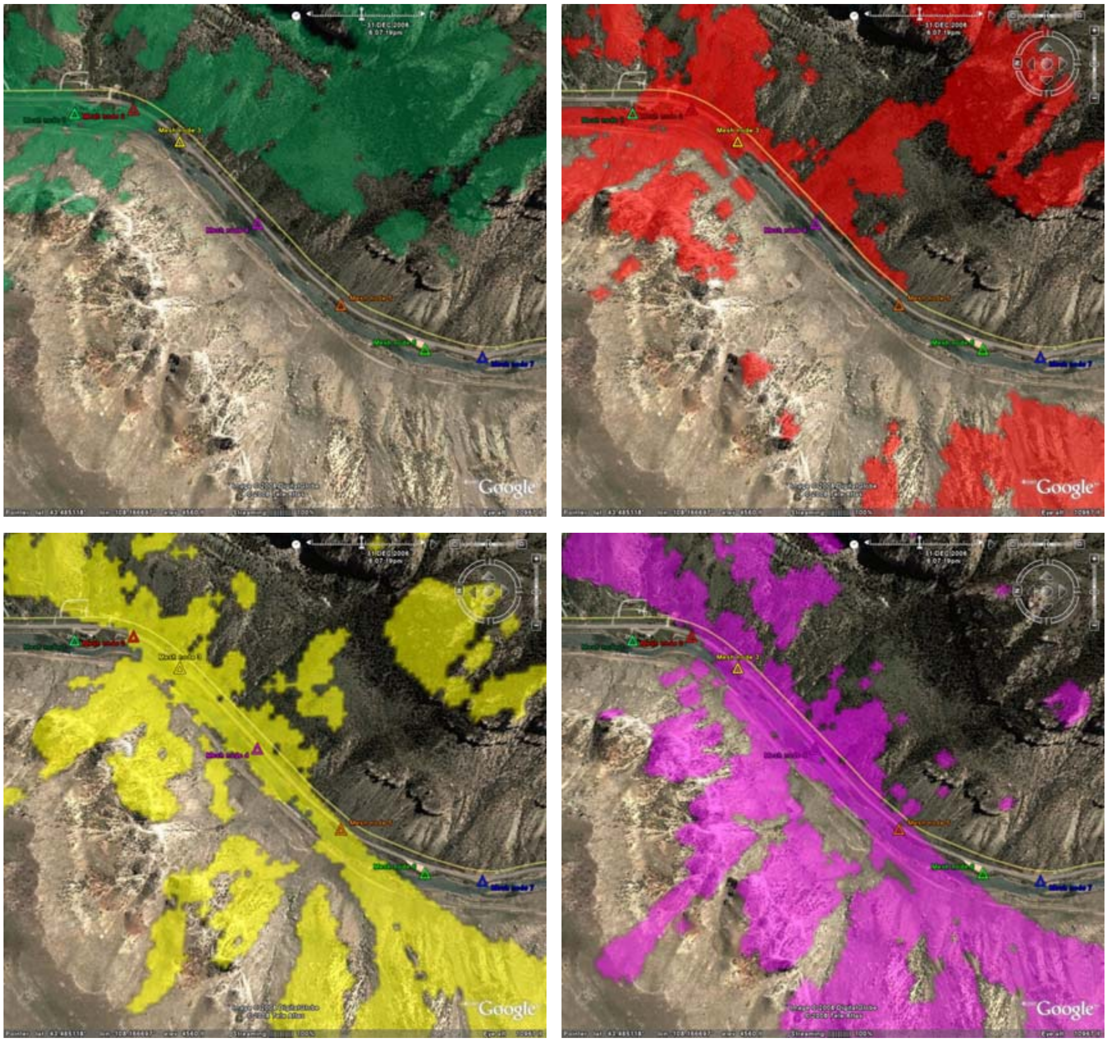

Figure 85: Design of Demonstration Network (Nodes 1–4).

10.7. Pre-Demonstration testing

On-site testing was conducted to select node locations for the demonstration (Figure 86). To prepare for testing, approximate locations were chosen by using the Radio Network Design Application. Based on a quick design limiting the number of nodes, it was estimated that three radios would be needed to bridge the distance between the second and third parking areas.

Figure 86: Wind River Canyon Test Network

Nodes were placed on the sides of the roadway in the exact location and height that would be used in the demonstration (Figure 87).

Figure 87: Pre-Demonstration On-Site Network Testing

View of pullout 2 is not possible from the pavilions, node 7, but by putting a MeshBox node on the shore of the river, node 6, connectivity to the rest of the network could be achieved. Refer to Table 14 for the corresponding node coordinates.

Table 14: Demonstration Network Node Locations

Node	Latitude	Longitude	Altitude
1	43.49275304	-108.1588562	4548
2	43.49241351	-108.1594386	4513
3	43.48865798	-108.1605262	4522
4	43.48749070	-108.1618864	4537

5	43.48453860	-108.1658559	4534
6	43.48235779	-108.1682883	4576
7	43.47953584	-108.1705172	4569

The on-site testing showed that a radio network could be built to cover the selected demonstration area. However, most of the ten MeshBox units were required to cover the site.

10.8. Demonstration Scenario and Script

A scenario was developed for the demonstration that specifically highlighted the self-forming and self-healing aspects of mesh networks. After consulting with Dave Larsen, the idea of a rock slide scenario was selected. Dave helped make the scenario realistic and defined placement and movement of responder units.

The simulated rock slide will block the roadway and units will enter the area from either the north (from Thermopolis) or the south (from Shoshoni). As the scenario progresses, and through the placement of more responder units, the network will form. At that time, the public safety applications for data networks will be demonstrated.

10.8.1. Demonstration Scenario

A rock slide occurs in the Wind River canyon. One lane of the roadway is blocked and there is a danger of more rocks falling. Hot Springs County Sherriff's Department, Thermopolis Fire Department, Thermopolis Police Department, and an ambulance have responded from the north and hastily set up an Incident Command Post (ICP). The Wyoming Highway Patrol and Boysen State Park have responded from the south. Traffic is stopped on both sides of the rock slide. A motorist on the south side of the rock slide is injured by falling rocks.

10.8.2. Simulated Responder Units

The simulated responder units include:

- Thermopolis Fire 1 – static unit at ICP
- Thermopolis Fire 2 – static unit at ICP
- Thermopolis Police – static unit at ICP
- Ambulance – mobile vehicle driven by WTI personnel
- Hot Springs County Sherriff – mobile vehicle driven by Hot Springs County personnel
- Wyoming Highway Patrol – static vehicle manned by WTI personnel
- Boysen State Park – mobile vehicle driven by WTI personnel

Figure 88: Planned Demonstration Site.

10.8.3. Demonstration Script

Thermopolis Fire 1, Thermopolis Fire 2 and Thermopolis Police have set up an ICP at a pullout north of the incident with a simulated command vehicle made up of a mesh node connected to a satellite communication system.

The ambulance is waiting at the command post to evaluate the situation. No data transmission is available through the incident area.

IC – HP, this is IC. We have an ambulance here to evacuate the injured party. Please advise of the situation.

HP – IC this is HP. The rock slide occurred between Pullout 1 and Pullout 2. Both pullouts are in a safe zone.

IC – Ambulance it is safe to move to Pullout 1. Please move there and wait for instructions.

The ambulance moves closer to the incident at Pullout 1. Upon reaching the pullout the ambulance makes a connection across the network. The entire network comes up and now data transmission is possible. *This demonstrates the self-forming aspect of mesh networks.*

IC – HP we have a data network. Please advise us of the situation.

HP – IC am marking the rock slide area on the mapping tab. I will upload pictures to the network.

HP marks the map to show where the rockslide took place. Also marks “One-Lane Blocked” through the area. HP uploads a picture of the rock face. On the image is marked “Large rock.” HSC Sherriff appears on the scene and drives to Pullout 1. HP grabs weather.

IC – Ambulance, HSCS has arrived and will assist you at your location. HP, we have received your markup and pictures. Tell us the condition of the large rock.

HP – IC, the large rock appears stable. I will transmit video of the slide area.

HP transmits video. Upon viewing of the video IC orders the ambulance across the rock slide area. HSCS arrives at Pullout 1.

IC – Ambulance this is IC. Proceed across the slide area to pick up the injured party. *This demonstrates the self-healing aspect of mesh networks.*

Ambulance – Roger, IC. We will proceed to the injured party.

The ambulance moves to Pullout 3 and parks.

IC – Ambulance this is IC. We show you at the injured party. Please advise.

Ambulance – IC, we have picked up the injured party. We will transport to Hot Springs County Hospital.

The ambulance turns around and drives (slowly if possible) back up the network and parks at the ICP.

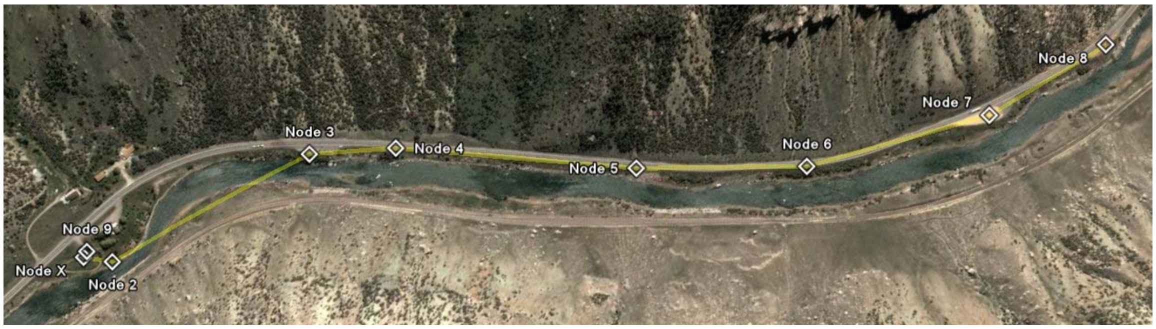

Figure 89: Locations of the Nodes for the Demonstration.

Note: Node X is a backup node.

10.9. Conclusions

The project team received significant assistance in planning the demonstration from Dave Larsen of the Hot Spring County Sheriff's Department. He posed a realistic scenario and helped the team to develop and present. Several key functionalities that were discussed in early meetings with stakeholders were incorporated into the demonstration. These included sharing photographs, sending and receiving video, mapping, automated vehicle location, and provision local weather information. This helped to assure credibility of the demonstration with the public safety officials who attended it.

Several key requirements were set forth early in the project for the demonstration. First, it needed to show the self-forming, self-healing aspects of mesh networks. Second, it should require zero or near-zero configuration by the end-users. In other words, it had to work automatically.

It was understood that the zero configuration requirement would be difficult to achieve, but that it was necessary for system acceptance. Thus, the scenario was constructed such that communication paths were well-known and viable. This fact would be presented to attendees.

11. DEMONSTRATION RESULTS

11.1. Demonstration Requirement

In the original proposal, Ad Hoc Routing for Rural Public Safety for SAFECOM Program (DHS-06-ST-086-006), it was proposed that a proof-of-concept demonstration would be a deliverable. An example network design and list of technology was presented, which served as a template for the design and the main points in the demonstration. Text from the proposal is provided below:

> In this project, we also plan to conduct a proof-of-concept demonstration. The demonstration scenario is illustrated in Figure 90. In this demonstration, we plan to have one desktop computer and six Windows-based laptop computers with 802.11g NICs. Two of the laptops will serve as end-user equipment and we will use Itronix Toughbook computers that run applications used by the public safety agencies. We will download the implemented routing protocols to each laptop computer. A mesh backbone network will be formed by two laptop computers to emulate a JAN. One of them will be chosen as the gateway node and will be directly connected with a wired Ethernet link, which is used to emulate the IP network in the dispatch central office. A MANET will be formed by the other four laptop computers to emulate an IAN and PAN. The desktop computer will be connected via Ethernet and used as a back-end database server. We plan to demonstrate our system using several popular public safety applications.
>
> - Database query application: We will open a database client on a mobile node to retrieve data from the database server on the Ethernet backbone network.
> - Voice application: We will establish a Voice-over-IP (VoIP) connection between a mobile node and the desktop computer in the dispatch center by using an instant messaging client.
> - Video application: We will establish a connection to transmit video frames captured by a video camera in a mobile node back to the desktop computer in the dispatch center.
> - Image application: We will establish a connection for image delivery of an image file from a digital camera attached to a mobile node in the PAN to the computer in the dispatch center.

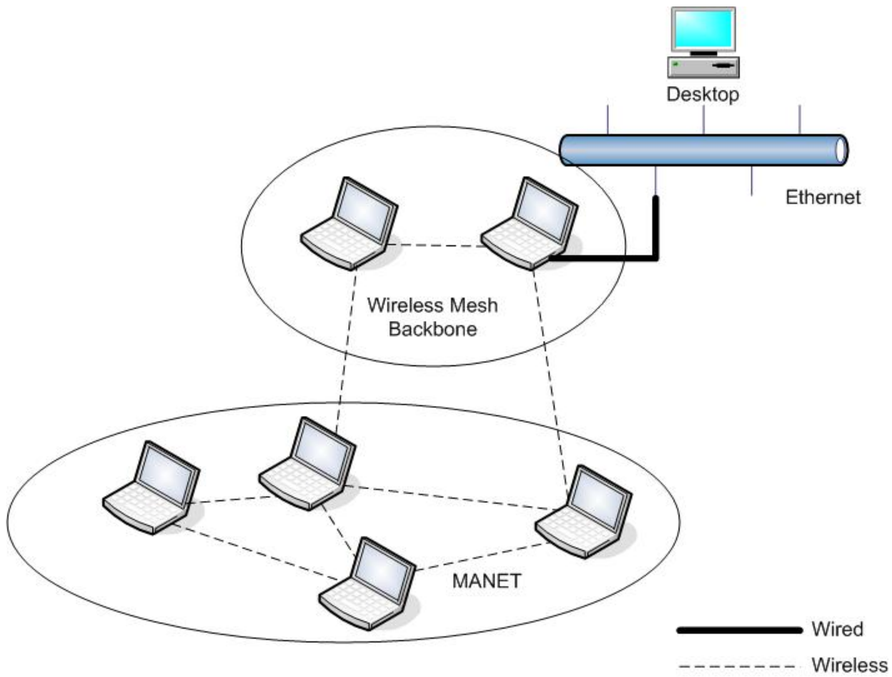

Figure 90: Proposed Demonstration Network.

The actual demonstration reflected the proposal but used more advanced and more realistic examples of equipment and technology. All the technology options from the proposal were demonstrated except a voice application. It was decided that a discussion of replacement of VHF radio technology by a VoIP application over a short-range broadband network would be a distraction to the demonstration.

11.2. Demonstration Results

The MeshBox system was used in a demonstration of mesh technology for public safety officials from Hot Springs County and the surrounding area on August 14, 2008.

The demonstration took place in a challenging stretch of the Wind River Canyon where the rim of the canyon is approximately one mile wide and the walls are 1,700 feet deep. At present, no outside radio communication is available in the selected location. The MeshBox system was used to provide communication between two parking areas on U.S. Highway 20. Vehicles equipped with MeshBox units moved into the parking areas and connected to stationary roadside nodes that provided links where distance and/or the geography limit communication.

The demonstration highlighted the self-forming and self-healing capabilities of a mesh network. The network was composed of four nodes. Two nodes were placed in static locations and two nodes were installed in vehicles. Data traffic was transmitted over the network from rugged laptop computers. Data types included video, images, weather, and vehicle global positioning system (GPS) location data.

The demonstration was attended by local and state public safety officials from Thermopolis, Basin, Shoshoni, Cheyenne, and Fort Washakie, Wyoming. The attendees varied in responsibility and position. Along with law enforcement and fire personnel, there were many attendees who were responsible for communications including dispatchers, communication supervisors, engineers, and program managers for the statewide communication system.

Overall, the technology and the demonstration itself were well received. The idea that data communications could occur with little to no “fiddling” was very appealing to all the attendees. The comment was made that the technology was such that one could just “flip a button and form a network.”

11.2.1. Demonstration Setup

11.2.1.1. Mesh Application

To demonstrate public safety applications of data traffic WTI used a custom-developed, peer-to-peer mesh application. The software was run on Panasonic Toughbook rugged tablet computers, Toshiba tablet laptop computers and other non-tablet laptop computers. Each mobile computer was attached to a GPS for location information and a MeshBox for network connectivity.

At the ICP there were three laptop computers that were used primarily for display of the application and were not connected to GPS. These nodes had their locations hard-coded and did not move during the demonstration. These laptops were passed around the crowd during the demonstration.

11.2.1.2. Video

During the demonstration video was served from a laptop computer connected to a video camera via IEEE-1394. The video was encoded in real time using Microsoft Windows Media Encoder 9.0. The video was viewed using the VideoLAN Client media player and shown at the demonstration area on a large LCD monitor.

The video's resolution was 640 by 480 pixels and encoded in WMV9 at four frames per second with a bit rate of 64 kilobits per second. The video transmission was reliable, exhibiting no interruptions during the demonstration.

11.2.1.3. Satellite Internet

A Hughesnet Satellite Internet system was set up at the ICP for connection to the Internet and a simulated connection to the JAN. A WTI-owned transportation research trailer was used at the ICP to provide power and wired and wireless local area network connectivity.

Initially the trailer was set up near the north side of the roadside shelters on U.S. 20 (left of the red minivan in Figure 91). The satellite terminal was set up in the southwest corner of the west shelter on the concrete slab (in front of the gray pickup in Figure 91).

Figure 91: Roadside Picnic Area off US 20 in Wind River Canyon.

Our assigned satellite's signal (G16) at 99W azimuth was quickly acquired and displayed signal strength of over 60 (a minimum of 30 is required to register the terminal with the satellite). A short time later it was noticed that the signal strength had dropped to 15. The dish was re-pointed several times but the signal strength would not come back over 18. It was decided that some trees in the foreground may have been affecting LOS so the dish was moved about 100 feet north away from the shelters and trees (just on the other side of the red minivan in Figure 91). After setting up the dish, re-pointing and troubleshooting for more than an hour without success, the dish was moved to a location near the river and the mesh network node (see Figure 92).

Figure 92: Satellite System Location.

Since this site was too far from the trailer for power, an emergency starting battery and inverter were used to power the satellite terminal. Even here, with no LOS problems, the satellite terminal would not access the satellite with enough signal strength for registration (a signal strength of 23 was the most that could be achieved). Since LOS was not a problem at this river's edge site, it was decided to try another transponder.

There are three transponders in the modem list for the G16 satellite to choose from, the 1210 MHz, 1230 MHz and 1250 MHz transponders. The 1210 MHz transponder was the one being used and was the same transponder used to test the satellite system in Montana. The 1230 MHz transponder was selected. This transponder displayed signal strength of 66 without re-pointing the dish and after the system registered and downloaded the update files, the Internet was available to the network. A possible explanation of the transponder issue is that transponders are allocated dynamically, so it is possible that the 1210 transponder was at capacity when we tried it in Wyoming so the transponder would not accept any more registrations but it was not when we used it in Montana.

For the demonstration, the trailer was deployed as close to the river dish site as practical and a 120-foot power cord and Ethernet cable were used to connect the dish site to the trailer (Figure 93).

Figure 93: Cables from the Command Post to the Satellite System.

11.2.2. Pre-Demonstration Testing Results

During the demonstration it was not possible to measure performance of the network. However, testing was done prior to the demonstration to choose locations for nodes. Figure 94 shows the locations of the network nodes used for testing performance of the network, and Table 15 shows the GPS coordinates of the nodes.

Figure 94: Locations for Network Performance Measurement.

Table 15: Demonstration Network Node Locations.

Node	Latitude	Longitude	Altitude
1	43.49275304	-108.1588562	4548
2	43.49241351	-108.1594386	4513
3	43.48865798	-108.1605262	4522
4	43.48749070	-108.1618864	4537
5	43.48453860	-108.1658559	4534
6	43.48235779	-108.1682883	4576
7	43.47953584	-108.1705172	4569

Table 16 shows bandwidth from each node to the others within the demonstration network. The values for bandwidth were calculated using the Netperf package for Freifunk and are averaged from three upload and three download measurements.

Table 16: Bandwidth between nodes for the Demonstration Network (Mbps).

Node/Node	2	3	4	5	6	7
1	10.87	2.03	0.62	0.53	0.49	0.36
2		3.93	0.72	0.56	0.44	0.31
3			1.68	0.89	0.53	0.48
4				2.76	1.33	0.88
5					11.53	3.40
6						7.10

The data points in the descending diagonal cells of Table 16 are single hop, point-to-point links and carry the most bandwidth. As the number of hops increases, the bandwidth of the link decreases drastically. Average bandwidth per hop is shown in Table 17.

Table 17: Bandwidth per Hop for the Demonstration Network.

Link Distance Hops	Average Bandwidth (Mbps)
1	6.31
2	1.67
3	0.65
4	0.48
5	0.40
6	0.36

Although performance of the radios should be based primarily on the distance between nodes, other factors such as Fresnel zone violation, vegetation, and terrain affected link bandwidth. Table 18 provides data on bandwidth related to distance and elevation change.

Table 18: Link Distance and Bandwidth.

Link	Distance between nodes (miles)	Elevation Difference (feet)	Bandwidth (Mbps)
Node 1 to Node 2	0.04	25	10.87
Node 2 to Node 3	0.27	9	3.93
Node 3 to Node 4	0.11	15	1.68
Node 4 to Node 5	0.29	3	2.76
Node 5 to Node 6	0.19	32	11.53
Node 6 to Node 7	0.23	7	7.10

11.2.1. Demonstration Details

During the demonstration, connectivity between Pullout 1 and Pullout 2 could not be achieved (Figure 95). As this connection was required to demonstrate the planned scenario, the network was reduced in size and the script abandoned. It was decided that the self-forming and self-healing aspects of a mesh network would be shown on a much smaller network. The basic scenario was left in place but instead of simulating a scenario, nodes were moved to different locations and the results watched on the Mesh Application mapping tab display. Video was transmitted from the Wyoming State Patrol node to show the roadway and movement of vehicles that were not within sight.

Figure 95: Planned Demonstration Network.

The demonstration started with the nodes as shown in Figure 96. Location of the nodes was shown using the Mesh Application (Figure 97).

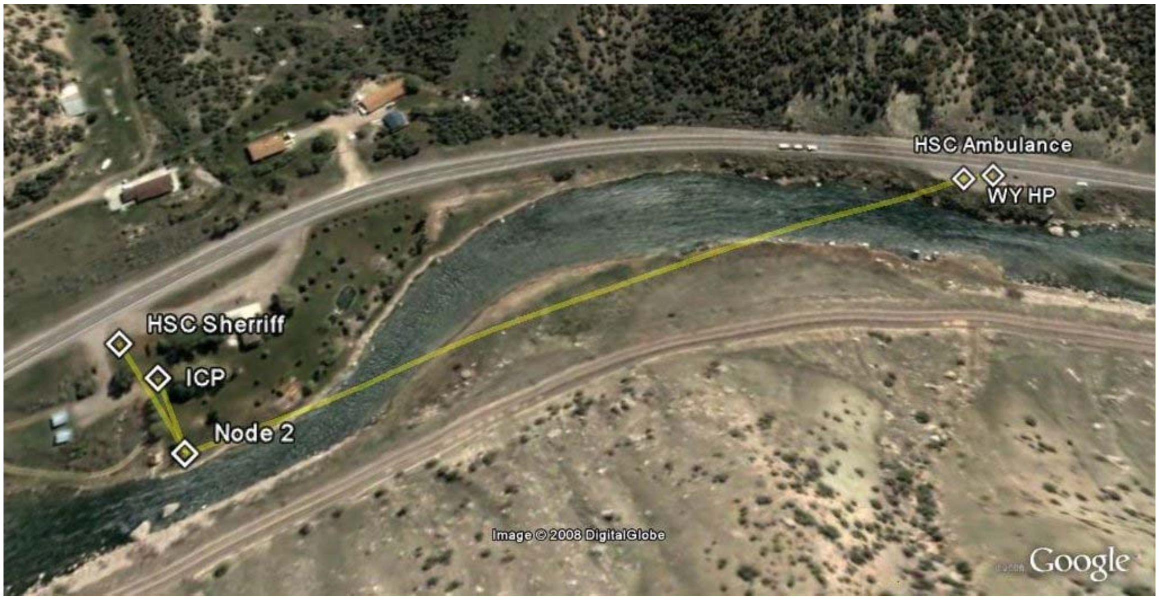

Figure 96: Initial Locations of the Nodes for the Demonstration.

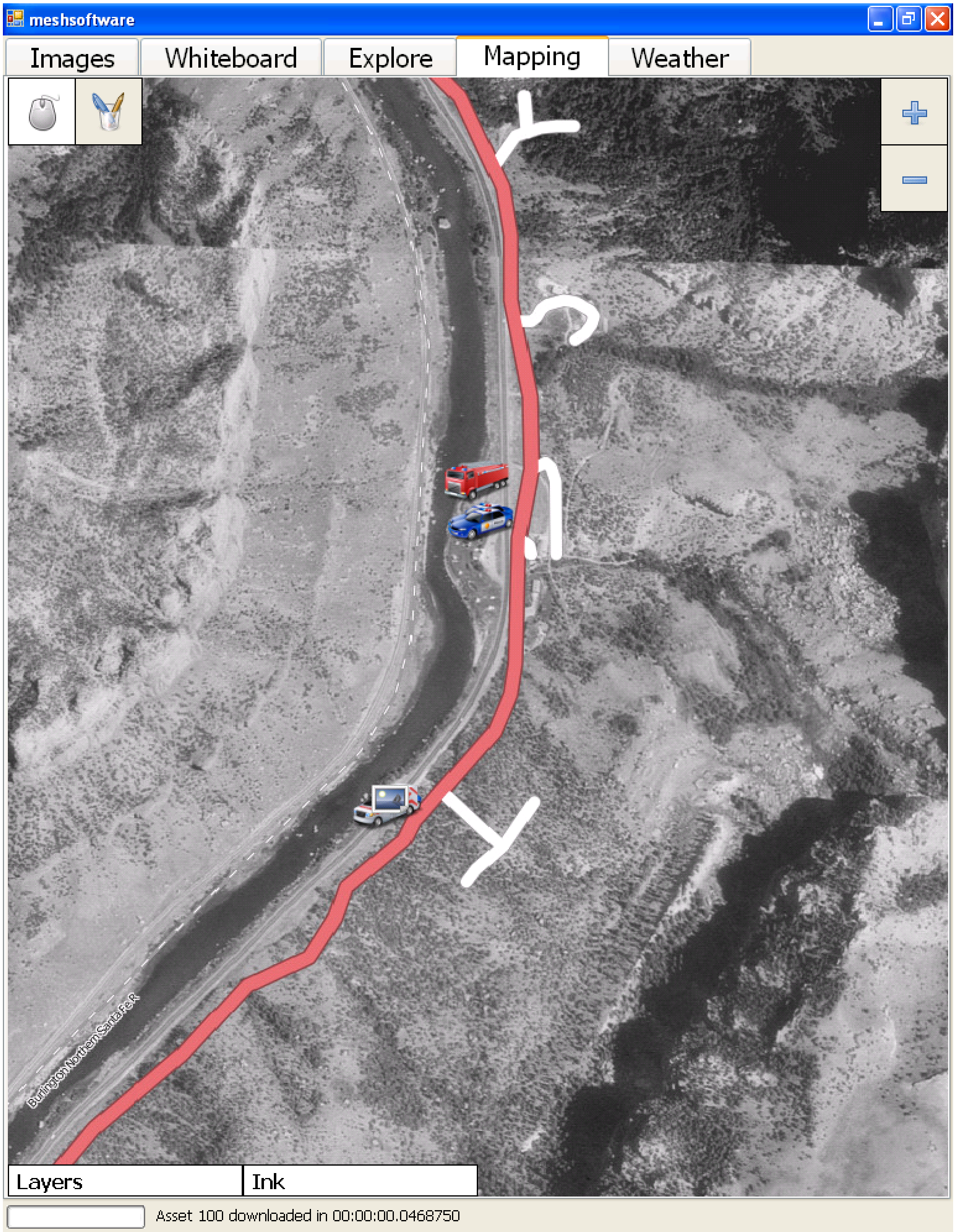

Figure 97: Mesh Application View at the Beginning of the Demonstration.

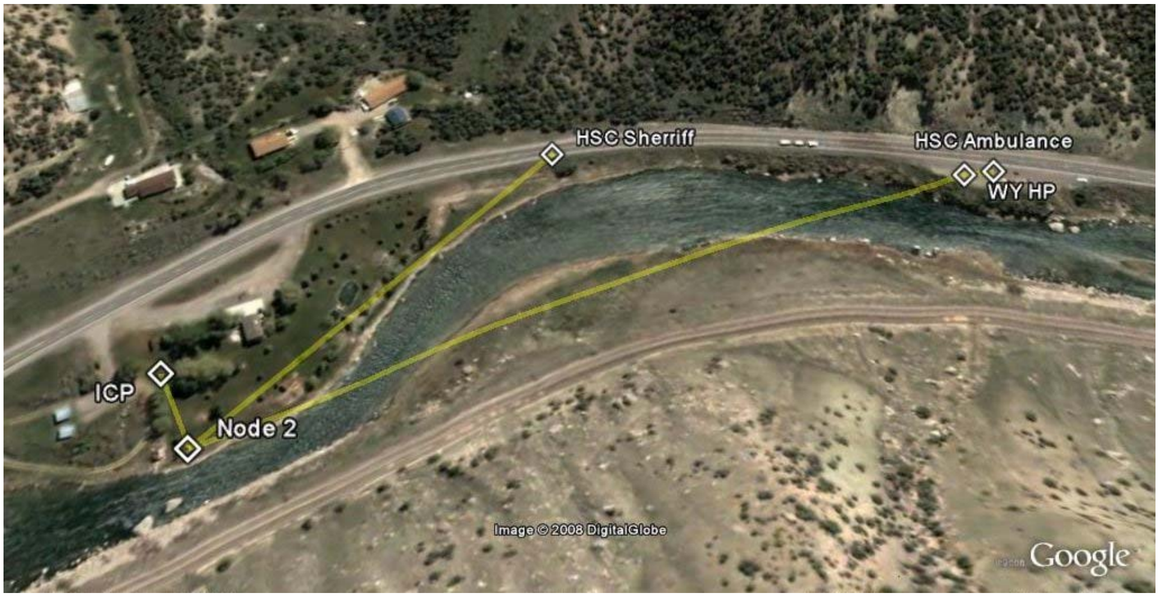

Figure 98: Demonstration of Self Healing Mesh Network Behavior.

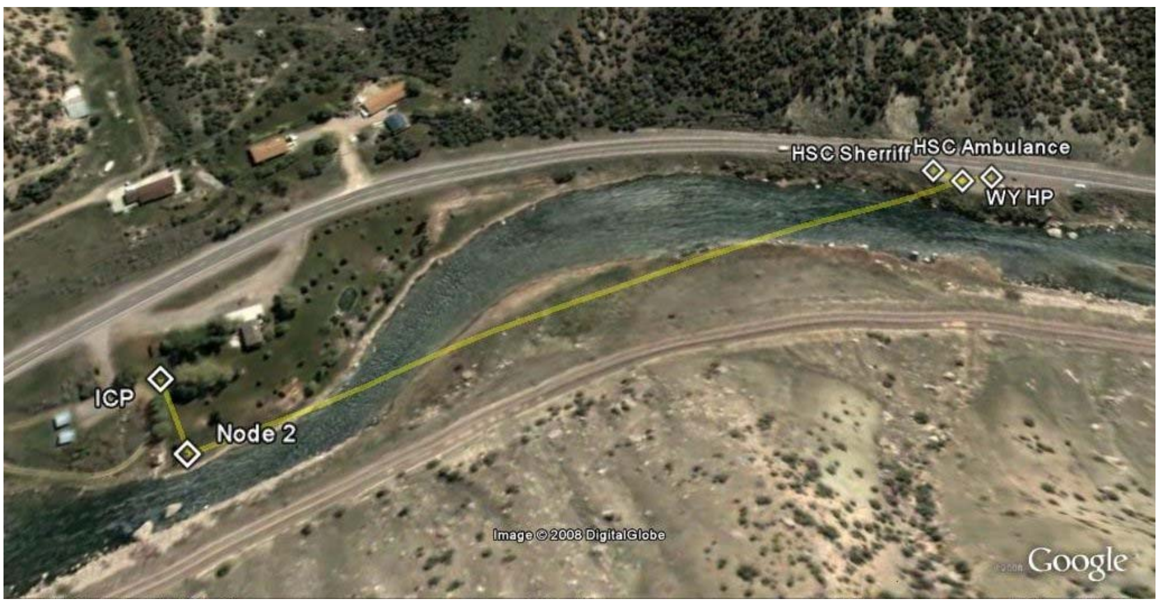

Figure 99: Demonstration of Self Forming Mesh Network Behavior.

Figure 100: Demonstration of Self Healing Mesh Network Behavior.

A. In the beginning of the demonstration Thermopolis Police, Thermopolis Fire, WyDOT, and HSC Sheriff were positioned at the ICP and Ambulance and WyHP were at pullout 1.
B. The demonstrators presented information about the project and then described the setup and equipment at the ICP and what was in the vehicles.
C. WyHP published a digital camera picture of the canyon wall.
D. The ambulance drew markup on the map to illustrate the rock slide area which was off the current view of the map. The demonstrators could not see the markup so it was requested that the Ambulance use markup to show the unit's location. The Ambulance drew markup to illustrate its location.
E. The demonstrators as Thermopolis Fire drew markup on the map to illustrate a rock slide area and illustrate use of the tablet pc.
F. HSCS moved his vehicle to Pullout 1. As the vehicle moved the map periodically updated the position of the icon. When the unit parked it reconnected to the units that were already in the parking area
G. HSCS added markup to the map to show where explosives were needed to remove rocks and rubble.
H. HSCS moved his vehicle back to the ICP. Progress of movement of the vehicle was watched on the mapping tab. When the vehicle came into range of Node 2 the mesh software connected directly to the node.
I. Ambulance moved the vehicle back to the ICP. Progress of movement of the vehicle was observed on the mapping tab. When the vehicle came into range of Node 2 the mesh software connected directly to the node.

12. CONCLUSIONS AND RECOMMENDATIONS

12.1. General Conclusions

The objectives of this study were met through the development of an extended protocol to meet QoS requirements, and through the demonstration of MANET technology to rural public safety stakeholders. The extended protocol, QASR, demonstrates that MANET routing protocols can achieve QoS requirements necessary to support public safety applications. Obviously, there are situations in which lack of infrastructure, difficult terrain, distance, vegetation and limitations of technology make data communication infeasible. However, MANET technology can be used to help at least partially in overcoming these challenges.

Critical to the development and evaluation of MANET technology for this application is having a suite of realistic and representative scenarios that can be used to test protocols and equipment. The project team worked closely with stakeholders through this project, particularly with the Hot Springs County Sheriff's Department. Rural public safety officials face numerous challenges that impose a number of practical limitations on the potential implementation of technologies like MANET. By understanding these limitations, it is possible to apply the technology to overcome challenges and work more efficiently.

It is recommended that further research and development be conducted to further the potential application of MANET technology to rural public safety. The extended protocol, QASR, may be appropriate for advancement to standardization through the IETF, with further evaluation and refinement (see below for further discussion). Other protocols may be developed to address QoS requirements, and they should be evaluated against scenarios similar to those documented in this project. As a further step in evaluation, it would be desirable to implement such protocols in field-ready equipment so that they can be used in live scenario evaluations. While it is possible to model the impact of terrain, vegetation, etc., in rural environments, real testing is necessary to confirm the readiness of such protocols and implementations for production use.

It was not feasible within the scope of this project to implement and test the extended protocol in conjunction with real communication hardware. This would be an immediate and natural extension of the work conducted in this project. Pilot testing with a stakeholder group such as the public safety officials from Hot Springs County could prove to be a very beneficial activity.

12.2. Recommendations Regarding IETF

The International Engineering Task Force (IETF) is the primary standards body addressing routing protocols (http://www.ietf.org/). In this project we have examined these activities and note that the current IETF standards activities are not addressing the key routing protocol features needed to meet the SoR requirements.

While the MANET WG has completed (at least to the experimental level) several routing protocols (e.g., DSR, AODV, OLSR and TBRPF), the assessment discussed elsewhere in this report indicates that these standards do not meet the public safety notional requirements. The current MANET WG efforts to develop DYMO and OLSRv2 are also lacking in several ways with respect to public safety requirements. We note here these gaps, as they are discussed elsewhere in this report.

1. None of the completed or pending protocols provide support for priority traffic flows.

2. None of the completed or pending protocols utilize location awareness to enable routing or resource utilization efficiencies.
3. None of the completed or pending protocols address quality of service requirements such as delay bounds.

The IETF is the proper forum for developing a protocol that meets the public safety notional requirements, and the results shown earlier in this report indicate that QASR is a good candidate for IETF consideration. AS QASR builds on DSR, a protocol already adopted by the IETF, it could be introduced to the MANET working group as an extension to the existing protocol. The process of proposing a protocol to the IETF and participating in the working group involves a time frame of several years and is beyond the scope of the current project. We recommend that this be taken into consideration for future work. Our intention, however, is to bring QASR to the attention of the technical community through presentation at IEEE conferences and publication in IEEE proceedings, which will give the new protocol visibility and initiate a dialog on QoS-aware routing that is designed to meet public safety needs.

13. APPENDIX – RECENTLY REPORTED RESULTS IN MANET AND VANET RESEARCH

Recently reported results in MANET and VANET research:

1. Routing with mobile relays in opportunistic sensor networks Ou, Chia-Ho (Department of Information Technology, National Pingtung Institute of Commerce); Ssu, Kuo-Feng Source: *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC, 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC'07*, 2007, p 4394684 Conference: 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC'07, Sep 3-7 2007, Athens, Greece Publisher: Institute of Electrical and Electronics Engineers Inc.

   Abstract: A route between the sensors and the sink in opportunistic sensor networks may have never existed. Traditional routing protocols cannot be directly applied to deal with the disconnection problem. This paper develops a mobile relay infrastructure approach to supporting data delivery in opportunistic sensor networks. Mobile relays cooperate to establish a routing infrastructure by modifying their trajectories. Unlike previous mobile infrastructure schemes, mobile relays move to specific positions and forward data instead of buffering and carrying data. The approach has been successfully implemented in the network simulator ns-2. The simulation results show that our infrastructure significantly improves the packet delivery rate. © 2007 IEEE. (21 refs.)

2. Autonomous messenger based routing in disjoint clusters of mobile sensor networks Hundewale, N. (Dept. of Comput. Sci., Georgia State Univ., Atlanta, GA, USA); Qiong Cheng; Xiaolin Hu; Bourgeois, A.; Zelikovsky, A. Source: *Proceedings of the 2006 Spring Simulation Multiconference (SpringSim'06)*, 2006, 57-64 ISBN-10: 1-56555-303-9, Conference: 2006 Spring Simulation Multiconference (SpringSim'06), 2-6 April 2006 , Huntsville, AL, USA Publisher: Society for Modeling and Simulation International, San Diego, CA, USA.

   Abstract: Most existing routing protocols in mobile ad hoc networks mainly focus on addressing the problems of dense and sparse yet connected networks. However, the crisis-driven and geography-driven applications typically challenge current routing protocols in disjoint mobile sensor networks (DMSN) where network partitions can occur and last for a significant period. In this paper, we apply agent-based simulation to studying the problems of efficient route discovery in the disjoint networks and present a novel autonomous messenger-based route discovery and routing protocol for disjoint clusters-based topology in DMSN. We have designed the framework for the route discovery and routing protocol. We design and implement two route discovery protocols, one based on straight line moving of messengers (SLMM) and the other based on flexible sharing policy of messengers (FSPM). Furthermore, we design the agent-based modeling and simulation in the application and implemented the prototype. The simulation of the framework prototype demonstrates that the route discovery and routing protocol based on FSPM increases network lifetime as compared to SLMM and also that FSPM exhibits higher data delivery than SLMM. (12 refs.)

3. A proactive data bundling system for intermittent mobile connections, Holman, Caitlin (Department of Computer Science, University of California, Santa Barbara); Harras, Khaled A.; Almeroth, Kevin C.; Lam, Anderson Source: *2006 3rd Annual IEEE Communications*

Society on Sensor and Adhoc Communications and Networks, Secon 2006, v 1, *2006 3rd Annual IEEE Communications Society on Sensor and Adhoc Communications and Networks, Secon 2006*, 2007, p 216-225, ISBN-10: 1424406269 Conference: 2006 3rd Annual IEEE Communications Society on Sensor and Ad hoc Communications and Networks, Secon 2006, Sep 25-28 2006, Reston, VA, United States Publisher: Institute of Electrical and Electronics Engineers Inc.

Abstract: As mobile and wireless technologies become more pervasive in our society, people begin to depend on network connectivity regardless of their location. Their mobility, however, implies a dynamic topology where routes to a destination cannot always be guaranteed. The intermittent connectivity, which results from this lack of end-to-end connection, is a dominant problem that leads to user frustration. Existing research to provide the mobile user with a mirage of constant connectivity generally presents mechanisms to handle disconnections when they occur. In contrast, the system we propose in this paper provides ways to handle disconnections before they occur. We present a Data Bundling System for Intermittent Connections (DBS-IC) comprised of a Stationary Agent (SA) and a Mobile Agent (MA). The SA proactively gathers data the user has previously specified, and opportunistically sends this data to the MA. The SA groups the user-requested data into one or more data bundles, which are then incrementally delivered to the MA during short periods of connectivity. We fully implement DBS-IC and evaluate its performance via live tests under varying network conditions. Results show that our system decreases data retrieval time by a factor of two in the average case and by a factor of 20 in the best case. © 2006 IEEE. (24 refs.)

4. Sensor data collection through gateways in a highly mobile mesh network Jenkins, A. (Dept. of Electr. & Comput. Eng., Colorado Univ., Boulder, CO, USA); Henkel, D.; Brown, T.X. Source: *2007 8th IEEE Wireless Communications and Networking Conference (IEEE Cat No. 07TH8918)*, 2007, 6 pp.ISBN-10: 1-4244-0659-5 Conference: 2007 8th IEEE Wireless Communications and Networking Conference, 11-15 March 2007 , Kowloon, China Publisher: IEEE, Piscataway, NJ, USA

   Abstract: Widely distributed sensors must discover paths back to data collection points possibly through sparsely connected and mobile networks. Current addressing and service discovery schemes in mobile networks are not well-suited to multihop disconnected networks. This paper describes an architecture and protocol for sensor data collection through highly mobile ad-hoc network (MANET) that may never experience end-to-end connectivity. Special gateway nodes are described which are responsible for intelligently routing messages to their intended destination(s). These gateway nodes qualify their links and announce their status to the MANET, a simple approach to service discovery that is effective in this implementation. The protocol is implemented and tested in a laboratory and outdoor environment. (15 refs.)

5. Opportunistic networking: Data forwarding in disconnected mobile ad hoc networks Pelusi, Luciana (IIT-CNR); Passarella, Andrea; Conti, Marco Source: *IEEE Communications Magazine*, v 44, n 11, November, 2006, p 134-141 ISSN: 0163-6804 CODEN: ICOMD9 Publisher: Institute of Electrical and Electronics Engineers Inc.

   Abstract: Opportunistic networks are one of the most interesting evolutions of MANET. In opportunistic networks, mobile nodes are enabled to communicate with each other even if a route connecting them never exists. Furthermore, nodes are not supposed to possess or acquire any knowledge about the network topology, which (instead) is necessary in traditional MANET routing protocols. Routes are built dynamically, while messages are en route between the sender and the destination(s), and any possible node can opportunistically be used as next hop, provided it is likely to bring the message closer to the final destination. These requirements make opportunistic networks a challenging and promising research field. In this article we survey the most interesting case studies related to opportunistic networking and discuss and organize a taxonomy for the main routing and forwarding approaches in this challenging environment. We finally envision further possible scenarios to make opportunistic networks part of the next-generation Internet. © 2006 IEEE. (20 refs.)

6. Hop ID: A virtual coordinate-based routing for sparse mobile ad hoc networks Zhao, Yao (Electrical Engineering and Computer Science Department, Northwestern University, Technical Institute); Chen, Yan; Li, Bo; Zhang, Qian Source: *IEEE Transactions on Mobile Computing*, v 6, n 9, September, 2007, p 1075-1089 ISSN: 1536-1233 Publisher: Institute of Electrical and Electronics Engineers Inc.

   Abstract: Routing in wireless communication systems such as ad hoc networks remains a challenging problem given the limited wireless bandwidth, users' mobility, and potentially large scale. Recently, a thrust of research has addressed these problems - the on-demand routing, geographical routing, and virtual coordinates. In this paper, we focus on geographical routing that has been shown to achieve good scalability without flooding; however, this usually requires the availability of location Information and can suffer from poor routing performance and severe dead end problems, especially in sparse networks. Specifically, we propose a new Hop ID routing scheme, which is a virtual coordinate-based routing protocol and does not require any location information. This achieves excellent routing performance comparable with that obtained by the shortest path routing schemes. In addition, we design efficient algorithms for setting up the system and adapt to the node mobility quickly and can effectively route out of dead ends. Extensive analysis and simulation show that the Hop ID-based routing achieves efficient routing for mobile ad hoc networks with various density, irregular topologies, and obstacles. © 2007 IEEE. (27 refs.)

7. Protocol design and optimization for delay/fault-tolerant mobile sensor networks Wang, Yu (Center for Advanced Computer Studies, University of Louisiana at Lafayette); Wu, Hongyi; Lin, Feng; Tzeng, Nian-Feng Source: *Proceedings - International Conference on Distributed Computing Systems*, *27th International Conference on Distributed Computing Systems, ICDCS'07*, 2007, p 4268164 CODEN: PICSEJ ISBN-10: 0769528376 Conference: 27th International Conference on Distributed Computing Systems, ICDCS'07, Jun 25-27 2007, Toronto, ON, Canada Sponsor: IEEE Comput. Soc. Tech. Committee on Distributed Proces. (TCDP) Publisher: Institute of Electrical and Electronics Engineers Inc.

   Abstract: While extensive studies have been carried out in the past several years for many sensor applications, they cannot be applied to the network with extremely low and intermittent connectivity, dubbed the Delay/Fault-Tolerant Mobile Sensor Network (DFT-MSN). Without end-to-end connections due to sparse network density and sensor node mobility, routing in DFT-MSN becomes localized and ties closely to medium access control, which naturally calls for merging Layer 3 and Layer 2 protocols in order to reduce overhead and improve network efficiency. DFT-MSN is fundamentally an opportunistic network, where the communication links exist only with certain probabilities and become the scarcest resource. At the same time, the sensor nodes in DFT-MSN have very limited battery power like those in other sensor networks. Clearly, there is a tradeoff between link utilization and energy efficiency. To address this tradeoff, we develop a cross-layer data delivery protocol for DFT-MSN, which includes two phases, i.e., the asynchronous phase and the synchronous phase. In the first phase, the sender contacts its neighbors to identify a set of appropriate receivers. Since no central control exists, the communication in the first phase is contention-based. In the second phase, the sender gains channel control and multicasts its data message to the receivers. Furthermore, several optimization issues in these two phases are identified, with solutions provided to reduce the collision probability and to balance between link utilization and energy efficiency. Our results show that the proposed cross-layer data delivery protocol for DFT-MSN achieves a high message delivery ratio with low energy consumption and an acceptable delay. © 2007 IEEE. (15 refs.)

8. (p,q)-Epidemic Routing for sparsely populated mobile ad hoc networks, Matsuda, Takahiro (Department of Information and Communications Technology, Graduate School of Engineering, Osaka University); Takine, Tetsuya Source: *IEEE Journal on Selected Areas in Communications*, v 26, n 5, June, 2008, p 783-793 ISSN: 0733-8716 CODEN: ISACEM Publisher: Institute of Electrical and Electronics Engineers Inc.

   Abstract: This paper considers (p,q)-Epidemic Routing, a class of store-carry-forward routing schemes, for sparsely populated mobile ad hoc networks. Our forwarding scheme includes Two-Hop Forwarding and the conventional Epidemic Routing as special cases. In such forwarding schemes, the original packet is copied many times and its packet copies spread over the network. Therefore those packet copies should be deleted after a packet reaches the destination. We analyze the performance of (p,q)-Epidemic Routing with VACCINE recovery scheme. Unlike most of the existing studies, we discuss the performance of (p,q)-Epidemic Routing in depth, taking account of the recovery process that deletes unnecessary packets from the network. © 2008 IEEE. (16 refs.)

9. Broadcasting in VANET Tonguz, Ozan (Carnegie Mellon University, ECE Dept.); Wisitpongphan, Nawaporn; Bai, Fan; Mudalige, Priyantha; Sadekar, Varsha Source: *2007 Mobile Networking for Vehicular Environments, MOVE*, *2007 Mobile Networking for Vehicular Environments, MOVE*, 2007, p 7-12 Conference: 2007 Mobile Networking for Vehicular Environments, MOVE, May 11 2007, Anchorage, AK, United States Publisher: Institute of Electrical and Electronics Engineers Computer Society

   Abstract: In this paper, we report the first complete version of a multi-hop broadcast protocol for vehicular ad hoc networks (VANET). Our results clearly show that broadcasting in VANET is very different from routing in mobile ad hoc networks (MANET) due to several reasons such as network topology, mobility patterns, demographics, traffic patterns at different times of the day, etc. These differences imply that conventional ad hoc routing protocols such as DSR and AODV will not be appropriate in VANETs for most vehicular broadcast applications. We identify three very different regimes that a vehicular broadcast protocol needs to work in: i) dense traffic regime; ii) sparse traffic regime; and iii) regular traffic regime. We build upon our previously proposed routing solutions for each regime and we show that the broadcast message can be disseminate efficiently. The proposed design of the Distributed Vehicular Broadcast (DV-CAST) protocol integrates the use of various routing solutions we have previously proposed. ©2007 IEEE. (17 refs.)

10. Probabilistic routing with multi-copies in delay tolerant networks Ze Li (Dept. of Comput. Sci. & Comput. Eng., Arkansas Univ., Fayetteville, AR, USA); Haiying Shen Source: *2008 28th International Conference on Distributed Computing Systems Workshops (ICDCS Workshops)*, June 2008, 471-6, ISBN-10: 978-0-7695-3173-1 Conference: 2008 28th International Conference on Distributed Computing Systems Workshops (ICDCS Workshops), 17-20 June 2008 , Beijing, China Publisher: IEEE, Piscataway, NJ, USA

    Abstract: Intermittently connected mobile networks don't have a complete path from a source to a destination at most of the time. Such an environment can be found in very sparse mobile networks where nodes meet only occasionally or in wireless sensor networks where nodes sleep most of the time to conserve energy. Current approaches in such networks are primarily based on two kinds of transmissions: multi-copy flooding scheme and single-copy forwarding scheme. However, they have either high overheads due to excessive transmission or long delays due to the possible incorrect choices during forwarding. In this paper, we propose a hybrid probabilistic routing algorithm using multi-copies called HUM, in which a packet is initially replicated to a certain number of nodes, which sequentially forward those packets to the destination node based on a probabilistic routing scheme. Simulations show that compared to Epidemic routing, Spray and wait routing, HUM routing scheme provides a nearly optimal delay performance with a stable packet arrive rate with the community mobility model. (26 refs.)

11. Research on data receiving and delivering in networks with long delays, Lei Liu (Inf. Inst. of Southwest, Univ. of Sci. & Technol., Mianyang, China); Hong Jiang Source: *Proceedings of the SPIE - The International Society for Optical Engineering*, v 6794, 10 Dec. 2007, 67944R-1-6 ISSN: 0277-786X CODEN: PSISDG Conference: ICMIT 2007: Mechatronics, MEMS, and Smart Materials, 5-6 Dec. 2007 , Gifu, Japan Publisher: SPIE - The International Society for Optical Engineering, USA.

    Abstract: An ad-hoc network is formed by a group of mobile hosts upon a wireless network interface. In the sparse mobile ad-hoc networks (SMANET), continuous end-to-end path between source and destination nodes, precedent condition of the traditional communication technology, may never exist. The disconnected or discontinuously connected networks and high link error rates pose a new set of challenges. The usual way to deal with this problem is to let the mobile computer wait for network reconnection passively, which may lead to unacceptable transmission delays. Although long range communication can be used to establish the link between nodes, it leads to rapid draining of nodes' limited batteries. In this paper, a kind of improved message relaying approach is proposed. Besides the function of route discovering, this approach is designed to realize data receiving and delivering (DRD) in networks with long delays. The data are stored and forwarded by the node chosen in the "node-choosing" procedure. With the help of the nodes' mobility, data can be relayed hop by hop from the source node (SN) to the destination node (DN). Consequently, the source node and the destination node can communicate to each other indirectly. It is believed that this scheme is useful for applications that require urgent message delivery and collect data in wild regions, such as emergency relief or field operations. (10 refs.)

12. Improving connectivity in vehicular ad hoc networks: An analytical study, Yousefi, Saleh (Computer Engineering Faculty, Iran University of Science and Technology); Altman, Eitan; El-Azouzi, Rachid; Fathy, Mahmood Source: *Computer Communications*, v 31, n 9, Jun 8, 2008, p 1653-1659 ISSN: 0140-3664 CODEN: COCOD7 Publisher: Elsevier

Abstract: Connectivity in vehicular ad hoc networks may degrade dramatically in sparse traffic and also high speed highways. In this paper we study a way to improve the connectivity by adding some extra nodes with higher transmission range which we call mobile base-stations. These nodes can also offer commercial services (e.g. advertisement, video, audio, etc.) to the vehicles on roads. Besides, the financial profit of those services also depends on a satisfactory connectivity. We use an equivalent M / G / infinity queuing model in order to investigate the connectivity. We further take into account the case when some vehicles do not participate in the network either because they are not equipped with wireless transceivers or some other reasons like security concerns. Moreover, connectivity in presence of fixed Road Side Units (RSUs) is also studied. Our proposed analytical model can be used to find the optimum values of the number of base-stations as well as their transmission range in order to achieve a desired degree of connectivity. © 2007 Elsevier B.V. All rights reserved. (12 refs.)

13. MURU: A multi-hop routing protocol for urban vehicular ad hoc networks, Mo, Zhaomin (Telecommunications and Information Technology Institute, Florida International University); Zhu, Hao; Makki, Kia; Pissinou, Niki Source: *2006 3rd Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services, MobiQuitous*, *2006 3rd Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services, MobiQuitous*, 2006, p 4141759, ISBN-10: 1424404991 Conference: 2006 3rd Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services, MobiQuitous, Jul 17-21 2006, San Jose, CA, United States Publisher: Institute of Electrical and Electronics Engineers Computer Society

    Abstract: Vehicular ad hoc networks (VANETs) are going to be an important communication infrastructure in our life. Because of high mobility and frequent link disconnection, it becomes quite challenging to establish a robust multi-hop path that helps packet delivery from the source to the destination. This paper presents a multi-hop routing protocol, called MURU, that is able to find robust paths in urban VANETs to achieve high end-to-end packet delivery ratio with low overhead. MURU tries to minimize the probability of path breakage by exploiting mobility information of each vehicle in VANETs. A new metric called expected disconnection degree (EDD) is used to select the most robust path from the source to the destination. MURU is fully distributed and does not incur much overhead, which makes MURU highly scalable for VANETs. The design is sufficiently justified through theoretical analysis and the protocol is evaluated with extensive simulations. Simulation results demonstrate that MURU significantly outperforms existing ad hoc routing protocols in terms of packet delivery ratio, packet delay and control overhead. ©2006 IEEE. (19 refs.)

14. Routing in sparse vehicular ad hoc wireless networks, Wisitpongphan, N. (Carnegie Mellon Univ., Pittsburgh, USA); Fan Bai; Mudalige, P.; Sadekar, V.; Tonguz, O. Source: *IEEE Journal on Selected Areas in Communications*, v 25, n 8, Oct. 2007, 1538-56 ISSN: 0733-8716 CODEN: ISACEM Publisher: IEEE, USA

    Abstract: A vehicular ad hoc network (VANET) may exhibit a bipolar behavior, i.e., the network can either be fully connected or sparsely connected depending on the time of day or on the market penetration rate of the wireless communication devices. In this paper, we use empirical vehicle traffic data measured on 1-80 freeway in California to develop a comprehensive analytical framework to study the disconnected network phenomenon and its network characteristics. These characteristics shed light on the key routing performance metrics of interest in disconnected VANETs, such as the average time taken to propagate a packet to disconnected nodes (i.e., the re-healing time). Our results show that, depending on the sparsity of vehicles or the market penetration rate of cars using Dedicated Short Range Communication (DSRC) technology, the network re-healing time can vary from a few seconds to several minutes. This suggests that, for vehicular safety applications, a new ad hoc routing protocol will be needed as the conventional ad hoc routing protocols such as Dynamic Source Routing (DSR) and Ad Hoc On-Demand Distance Vector Routing (AODV) will not work with such long re-healing times. In addition, the developed analytical framework and its predictions provide valuable insights into the VANET routing performance in the disconnected network regime. (27 refs.)

15. VADD: Vehicle-assisted data delivery in vehicular Ad hoc networks, Zhao, Jing (Department of Computer Science and Engineering, The Pennsylvania State University); Cao, Guohong Source: *IEEE Transactions on Vehicular Technology*, v 57, n 3, May, 2008, p 1910-1922, ISSN: 0018-9545 CODEN: ITVTAB Publisher: Institute of Electrical and Electronics Engineers Inc.

    Abstract: Multihop data delivery through vehicular ad hoc networks is complicated by the fact that vehicular networks are highly mobile and frequently disconnected. To address this issue, we adopt the idea of carry and forward, where a moving vehicle carries a packet until a new vehicle moves into its vicinity and forwards the packet. Being different from existing carry and forward solutions, we make use of predictable vehicle mobility, which is limited by traffic pattern and road layout. Based on the existing traffic pattern, a vehicle can find the next road to forward the packet to reduce the delay. We propose several vehicle-assisted data delivery (VADD) protocols to forward the packet to the best road with the lowest data-delivery delay. Experimental results show that the proposed VADD protocols outperform existing solutions in terms of packet-delivery ratio, data packet delay, and protocol overhead. Among the proposed VADD protocols, the Hybrid Probe (H-VADD) protocol has a much better performance. © 2007 IEEE. (23 refs.)

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