Final Report for the project entitled:

4W1746 Communication Briefcase

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LIST OF ABBREVIATIONS

BW	Bandwidth
dB	Decibel
dBm	dB relative to 1 milliwatt
Cat 5	Category 5 Ethernet cable
DHCP	Dynamic Host Configuration Protocol
DNS	Domain Name Server
GPL	General Public License
ITS	Intelligent Transportation Systems
LAN	Local Area Network
LED	Light Emitting Diode
MANET	Mobile Ad-hoc Network
MSU	Montana State University
NiMH	Nickel Metal Hydride
OLSR	Optimized Link State Routing
QoS	Quality of Service
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
SNR	Signal to Noise Ratio
Tx	Transmit
UPS	Uninterruptable Power Supply
VPN	Virtual Private Network
WAN	Wide Area Network
Wi-Fi	Wireless Fidelity
WTI	Western Transportation Institute

EXECUTIVE SUMMARY

The purpose of this project was to design and implement a prototype "communications briefcase" for transportation applications in remote rural areas. The original concept was to develop a briefcase that would serve as a gateway to the Internet, providing access to multiple users via a cellular data connection. The concept was changed to investigate instead the potential for multiple devices to provide mesh networking capabilities in similar remote rural areas.

An off-the-shelf, consumer-grade router was selected as the primary component for the system, with an enclosure to support the router, as well as a power management system that was custom-developed to manage a set of rechargeable batteries within the enclosure. Flexibility was provided by using various external antennas, including magnetic mount antennas for vehicular operation. The resulting units were called "MeshBoxes" and 10 units were constructed for research and demonstration purposes.

The MeshBoxes were demonstrated to transportation professionals at several venues and were well received, although they represented only a first prototype. The principal demonstration of the MeshBoxes occurred during a Department of Homeland Security funded project to demonstrate a mobile, ad-hoc network (MANET) to public safety officials from Wyoming. In conjunction with a rockslide scenario, the MeshBoxes were used to provide connectivity among several simulated and real public safety vehicles. Video was served over the network along with several collaborative applications. Internet access was provided via a satellite connection.

During the Wyoming demonstration it was discovered that there was noticeable variation in the performance of the MeshBoxes despite the fact that they were configured identically. Subsequent testing was conducted to determine viable link distances for node-to-node communication. Additional factors such as antenna type were taken into consideration.

Ultimately it was determined that much of the observed variability could be attributed to the use of consumer-grade equipment and the battery power of the MeshBoxes. Unfortunately, no industrial equipment was available at the time to provide the same flexibility for research and development in an open, Linux-based system, so there was no apparent alternative. Commercial proprietary mesh networking systems are available, and these could be considered for production deployments.

This project demonstrated that there is applicability of mesh networks to transportation and public safety in remote rural areas. Possible applications include remedies for problems with fixed infrastructure such as sensor networks, as well as a variety of mobile applications.

1. INTRODUCTION

Recent research in intelligent transportation systems and public safety communication has identified mesh and linear (serial) multi-hop topologies as an alternative to traditional wired networks and point-to-point and point-to-multipoint radio frequency (RF) communication network topologies. Mesh networks may provide advantages over traditional systems when used in certain transportation and public safety applications. Multiple low-cost communication nodes can be used instead of, or in conjunction with, traditional RF tower or wired/fiber networks. When systems must provide communication coverage of a roadway for applications such as Connected Vehicle Research, mesh or linear multi-hop networks can carry both local network and backbone traffic on one system.

Data communication in rural areas presents numerous challenges for both fixed and mobile deployment. At present, department of transportation staff either have no equipment for data communication in these areas, or have separate, redundant equipment for multiple service providers. A Mobile Communications Briefcase, as envisioned in this project, would provide, in a small and portable form factor, a communications platform that would be of general use for transportation applications and related research in both rural and urban settings.

In particular, the system could be applied to safety and operations applications for ITS development/evaluation and incident management. The Western Transportation Institute (WTI) has investigated, with Caltrans, the use of portable systems for delay time estimates in rural work zones. The communications briefcase could be used to provide communication capability within the work zone and from the work zone to a central server via a gateway node for general dissemination of traveler information. The briefcase could also be used as a general communications device for mobile data terminals used by first responders.

A fixed-location mesh network could be applied to road ecology applications for the transmission of data collected in the field by monitoring and detection systems such as those previously deployed on US 191, at WTI's Lewistown, Montana, test-bed, and other locations. At present, many of the systems deployed in these and similar areas require downloading data directly from units in the field and physically transporting the downloaded data to office workstations, etc., for analysis and redistribution. The briefcase could be used to upload collected data directly from field locations to central repositories.

The system could also be applied to mobility and public transportation, transportation planning, economics and freight management. For instance, automated vehicle location (AVL)-based systems could be rapidly prototyped and demonstrated using the communications briefcase to provide general communications capability. Applications include routing, traveler information, toll collection, etc.

The Systems Engineering Development and Integration Group at WTI researches communication challenges in rural areas where mesh networks are applicable, and strives to provide workable solutions to our sponsors and fellow researchers. The researchers saw the need for a mesh network communication system for the purposes of:

- Rapidly deploying temporary communication networks,
- Providing redundant communication systems for mobile and fixed ITS research equipment,
- Demonstrating the features of mesh networks, and

- Researching mesh networking operation and capability.

The resulting system was called, “MeshBox.”

Figure 1: Prototype Mesh Nodes

Ten nodes were assembled for the MeshBox system—seven are orange and three are yellow. The yellow nodes differ from the orange nodes by the addition of an external WAN port connector for accessing the Internet.

2. APPROACH

The initial goal of the project was to determine if the mobile communications briefcase system is viable using an open architecture and COTS equipment.

The specific objectives of this project were to:

1) Determine the utility and requirements of a mobile communications system/briefcase for transportation applications;
2) Identify standard, commercial off-the-shelf technology for prospective use in the system;
3) Determine modular designs for flexible integration of hardware and software;
4) Develop two instances of the system—two briefcases;
5) Document results of testing and evaluation with specific applications; and
6) Post design/blueprints of system in accord with open system/open source practices (via wiki or similar outlet).

The specific outcome of the project was a system that would consist of integrated cellular radios/modems, networking equipment (switch/router/bridge), GPS, and associated antennas, connectors, power source, etc.

The project goals were subsequently modified to focus specifically on mesh technology as applied to rural transportation and public safety needs. As such, there was a reduced emphasis on cellular technology in favor of a general capability for integration of the mesh network with a gateway network, which would provide access to the Internet or a private network. The gateway could be accomplished using cellular, satellite, or other wireless technologies, as well as wired connectivity. More than two instances of the system were necessary for the testing of mesh network communication, and the objective was modified accordingly to develop approximately 10 instances of the MeshBox. The system was tested in a rural safety application—providing a mobile, ad-hoc network (MANET) for an incident in a remote rural area.

3. MESHBOX DESIGN

For the MeshBox, the project team used a consumer wireless router running custom firmware to create a mesh radio and router. A router is a special purpose computer that intelligently transmits or routes data packets on a network or between multiple networks. Consumer routers commonly have a port for wide area network (WAN) connection, four or five ports for local area network (LAN) connection and, in the case of wireless routers, an 802.11 radio for multiple simultaneous wireless clients. A block diagram of the components is shown in Figure 2 below.

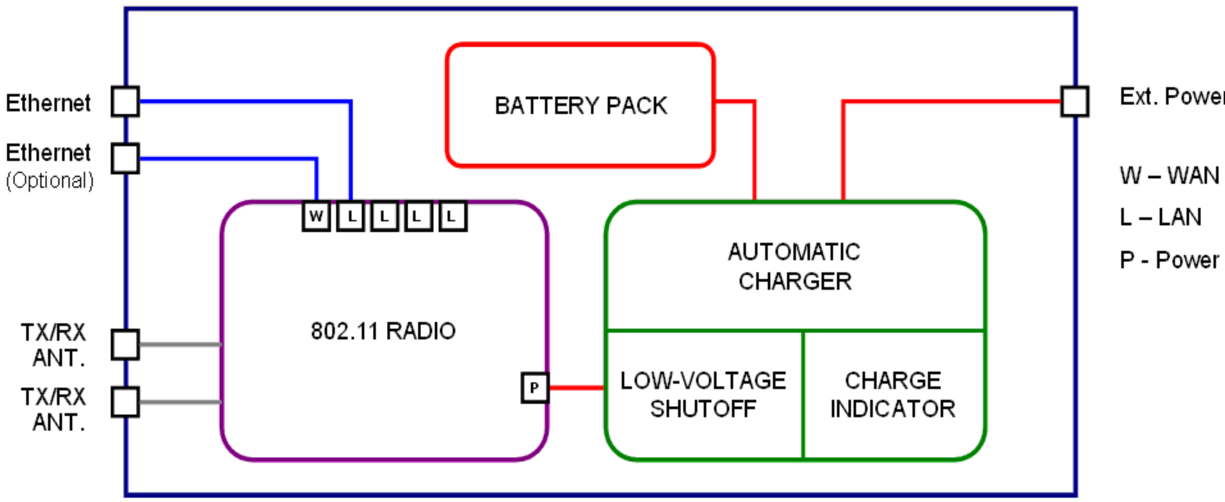


Figure 2: MeshBox Components

3.1. Hardware

Because the researchers are focused on real-world transportation applications and field deployment, a rugged, waterproof enclosure was selected to allow use of the MeshBox in extreme conditions. The enclosure contains a nickel metal hydride (NiMH) battery pack that can provide approximately six hours of power. A custom circuit board is installed that allows charging of the battery pack and protection from over-discharge of the battery pack, and that includes a battery capacity indicator. The components are shown in Figure 3.

Figure 3: Open MeshBox

3.1.1. Case

Based on previous experience packaging hardware for research, the researchers decided to use a hard plastic, waterproof case made by Pelican™ to house the RF equipment. 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.

3.1.2. Router

Routers have a processor, volatile and non-volatile memory, an operating system, services that run on top of the operating system, and generally a web-based user interface. Due to the requirements of network connectivity and a web-based user interface (which requires a light-weight web server), many manufacturers have used Linux as the operating system. The software on the router is called firmware and contains the operating system that performs basic network routing functions. The firmware also includes application software such as a firewall, a virtual private network (VPN) server and/or client, a DHCP server, a hotspot portal, the user interface, and software to provide access restriction and record network activity logs.

Use of a consumer router met our requirements of being affordable, having multiple Ethernet (LAN and WAN) jacks, and having a wireless IP-based radio. Further, the routers selected used a Linux-based firmware for which the researchers had prior experience. Normally, the firmware for off-the-shelf routers is proprietary and not extendable.

3.1.3. Antennas

Dual external N-type antenna connectors are provided for connection of directional or omni-directional antennas. Several types of antennas are available with N-male connectors and connect directly to the MeshBox, eliminating the need for cables. Cabled antennas can be attached for long distance use or when the MeshBox is in a vehicle. An inexpensive 7 dBi, omni-directional antenna was chosen for stock use. Other antennas used with the system include a 7 dBi omni-directional with a magnetic vehicle mount, a 12 dBi 34-degree panel antenna, and a 14.5 dBi 30-degree Yagi antenna.

3.1.4. Battery Pack

NiMH batteries were chosen for their 5000 milliampere-hour capacity and because they are less expensive than lithium-ion batteries. The C-type cells are installed in battery holders, instead of a welded battery pack, for easy single failed cell replacement.

3.1.5. Automatic Battery Charger

A charging circuit is built into the MeshBox, so there is no need to remove the batteries in order to charge them. By using the power connector on the outside of the box, the batteries can be charged while keeping the lid closed. The radio can be operated during charging.

The MeshBox is designed to be charged from the auxiliary power outlet in a vehicle. Since the charging circuit requires a supply voltage of 1.5V higher than the batteries, the MeshBox contains eight batteries to allow charging by a vehicle’s electrical system. Transient-voltage suppression is included to protect the radio from spikes in the vehicle power system.

3.1.5.1. Low Voltage Shut-Off

NiMH batteries can be damaged by over-discharging.[1] This can cause a pressure buildup in the cell that results in hydrogen gas being vented and permanent reduction of the battery capacity. In order to prevent damage to the batteries, a low-voltage shut-off circuit was designed that cuts power when voltage drops below 1.16V per cell.

3.1.5.2. Battery Charge Indication

A battery gauge is provided as a convenience. When pushed, a button energizes a circuit that lights segments in a light emitting diode (LED) bar-graph display to indicate battery charge state. Ten lit LED's indicate a full charge.

3.2. Software

The project team had frequently used Linksys WRT54GL routers running various derivatives of an open source firmware called OpenWRT[2] during the development, testing, and implementation of previous projects. OpenWRT is an open source router firmware that can be installed on a wide range of hardware platforms.

3.2.1. OpenWRT

OpenWRT originated from the Linksys WRT54G, which was based upon embedded Linux. Since Linux is released under a GNU General Public License (GPL), Linksys was required to release the source code for the firmware.[3] Using the Linksys source code for the router, a community formed to extend and improve the router’s feature set.

OpenWRT allows users to install packages to add features such as VPN, DNS, bandwidth monitoring, QoS routing and many other features. While OpenWRT offers various mesh routing packages, none are simple to configure, set up or maintain.

3.2.2. Freifunk

A firmware founded with the intent to create city-wide mesh networks[4] provided a simple to configure mesh implementation. The Freifunk[5] firmware is a customized version of OpenWRT designed specifically for mesh networking. The software integrates a well-tested mesh routing protocol (Optimized Link State Routing) with an easy-to-use interface, integrated gateway (WAN) management, and system status monitoring. Like its parent, OpenWRT, Freifunk has a wide variety of packages available to expand its initial feature set.

Testing with Freifunk demonstrated self-forming, self-healing network characteristics after an initial brief configuration. While Freifunk’s documentation is almost exclusively written in German, the researchers were assisted greatly by the excellent *Building a Rural Wireless Mesh Network*[6] guide by the Meraka Institute.

Freifunk can be installed on a number of hardware platforms. After a review of the available platforms, the Motorola WR850G[7] v3 was selected as the MeshBox router board based on size, power, and cost requirements. We note that this model had been discontinued by Motorola, so it was necessary to procure previously used devices.

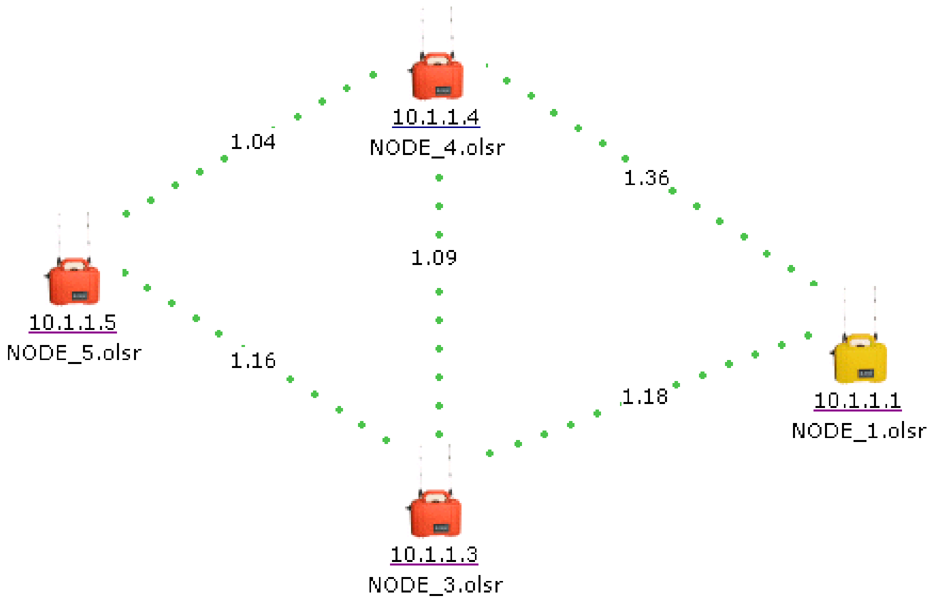


Figure 4: Freifunk Network Visualization Application

3.2.3. Optimized Link State Routing

Optimized Link State Routing (OLSR) is a mesh protocol originally developed by INRIA[8] and specified in IETF rfc3626[9] as an IP routing protocol optimized for mesh networking. OLSR was built from the ground up to be a scalable protocol and the latest version of OLSR has performed well in networks exceeding 2000 nodes.[10]

OLSR is a proactive routing protocol. It continually evaluates all links in a network and chooses routes with the best quality metric. In testing by the research team, OLSR has been proven to create usable stationary multi-hop mesh and linear networks such as in a roadside LAN. Adjusting OLSR parameters helped improve its performance in mobile applications.

4. SYSTEM TESTING

The MeshBox communication system was initially demonstrated in 2008 at the Western States Forum in California and for the Department of Homeland Security-funded MANETS project in the Wind River Canyon of Wyoming in August 2008. Following the demonstration in Wyoming, formal range testing of the MeshBox system was initiated. The following section describes the testing and results.

4.1. Western States Rural Transportation Technology Implementers Forum, Mt Shasta, CA

The MeshBox system was demonstrated to transportation technology professionals during the 2008 Western States Rural Transportation Technology Implementers Forum in Mount Shasta, CA. Nodes were deployed around the Mount Shasta Resort, with Internet connectivity provided by a WTI trailer using an EV-DO cellular modem. The conference room where the forum was being held was a small distance away, but the resort's walls decreased the wireless signal such that it required a number of nodes in a serial network to reach the conference room. The MeshBox demonstrated the self-forming and self-healing aspects of mesh networks with a series of nodes in a path to the conference room. The network formed a five-hop mesh with Internet connectivity. A number of the transportation professionals’ present displayed interest in the system with some requesting MeshBox units for testing.

4.2. Wind River Canyon, Hot Springs County, WY

The MeshBox system was used in a demonstration of mesh technology for public safety officials from Hot Springs County, WY, and the surrounding area in August 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 that time, no outside radio communication was available in the selected location. The MeshBox system would be used to provide communication between four parking areas on U.S. Highway 20. Vehicles equipped with MeshBox units would move into the parking areas and connect to stationary roadside nodes (MeshBox radios) that provide links where distance and/or the geography limit communication.

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

Figure 5: Wind River Canyon Test Network

To select a location for nodes in the demonstration, preliminary on-site testing was conducted (Figure 5). To prepare for testing, approximate locations were chosen by using a Radio Network Design Application that was developed in-house at WTI. Based on a quick design limiting the number of nodes, it was estimated that three nodes would be needed to bridge the distance between the second and third parking areas. In Figure 5, Node 5 is located in the second parking area and Node 1 is located in the third parking area. Refer to Table 1 for the locations of nodes for preliminary testing.

Table 1: 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 2: Bandwidth between Nodes for the Demonstration Network (Mbps) shows measured bandwidth from each node to the others within the network. The values for bandwidth were calculated using the Netperf package for Freifunk and are averaged over three upload and three download measurements.

Table 2: 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 2 are single hop, point-to-point links and carry the most bandwidth. As the number of hops increases, the bandwidth of the path decreases drastically. Average bandwidth per hop is shown in Table 3.

Table 3: 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

Link distance also affects bandwidth, and the sequential link distances and measured bandwidth are shown in Table 4.

Table 4: 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

The measurements for bandwidth were taken with the nodes placed at approximately six feet from the edge of the highway at a height of seven feet. The MeshBox units were attached to the backs of roadside delineator posts on the outside of a guard rail (Figure 6). Vehicular traffic such as trucks caused blockages of line of sight. The link between Node 6 and Node 7 was possibly affected by the presence of two large metal pavilion roofs. The link between Node 5 and Node 6 had limited Fresnel zone violation likely improving its performance compared to links near the roadway.

Figure 6: Gary Schoep (left) and Justin Krohn (right) from WTI Position MeshBoxes for Testing Prior to the MANETS Demonstration

The data collected was considered preliminary and the project team intended to collect further data during the demonstration and subsequent testing. At that point, the reasons for variation in the network's performance could only be conjectured. Data sufficient to characterize anticipated general use and best practices was still needed.

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

The simulated rock slide would block the roadway and units would enter the area from either the north (from the town of Thermopolis) or the south (from Shoshoni). As the scenario progressed and more responder units were in place, the network formed. At that time, several public safety applications for data networks were demonstrated.

Simulated responder units included seven vehicles:

- Thermopolis Fire 1 – static unit at Incident Command Post (ICP)
- Thermopolis Fire 2 – static unit at ICP
- Thermopolis Police – static unit at ICP
- Ambulance – mobile vehicle driven by WTI personnel
- Hot Springs County Sheriff – 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

The following script was followed for the demonstration:

- 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 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 7: Node Locations in Wind River Canyon for the MANETS Demonstration

In general, the demonstration worked in showing the self-forming, self-healing aspects of mesh networks with application to a public safety scenario. However, there was noticeable variation in the performance of the system and individual MeshBoxes. The source of this variation was not known, but it was suspected to be at least partially due to the components and construction of the MeshBoxes. In particular, the battery packs and associated power components were suspected of causing problems.

Subsequently, the project team would conduct tests in Bozeman to evaluate the link performance of MeshBox nodes and would bypass the power components of the system, opting instead for more reliable, external batteries. The tests were conducted in large part to characterize the performance of the other components of the MeshBoxes—the routers, antennas, etc. No further mesh testing was conducted as part of the project, with remaining tests focusing on point-to-point (node-to-node) connections that could be better isolated and characterized.

4.3. Node-to-Node Distance Tests

To address a number of factors, including potentially long link distance and desired low interference, MeshBox performance was tested at several locations. Testing started on the MSU campus near WTI. This area is characterized by a number of small office buildings, the MSU football stadium, other buildings on the MSU campus, and several open fields on and off campus. Due to interference concerns testing was moved into Hyalite Canyon in the Gallatin National Forest. This area is densely wooded, with a lightly used, two lane paved road following a creek and little other infrastructure or development. Winter snow stopped further testing in the canyon and personnel changes delayed further testing until October of the following year. Testing resumed in a large field south of WTI but the farmer planted the field with winter wheat, which precluded further testing at that site. A site on Durston Avenue in a moderately-developed area west of Bozeman was chosen next due to its size and the levelness of the area but it turned out that soccer fields at the site were quite active, requiring yet another move. Finally a site along 27th Avenue (another moderately developed area, with a mix of commercial and residential sites) was chosen for the final testing.

Descriptions of the testing at the chosen sites follow and unless otherwise stated, distances were measured with a measuring wheel. Note that node and MeshBox are used interchangeably in the following sections.

4.3.1. Montana State University, October 2008

On October 27, 2008, testing was performed near 11th Avenue on the campus of Montana State University (MSU) in Bozeman. The area around this portion of 11th Avenue is flat and largely characterized by farm fields and sparse construction, and showed little noticeable WiFi interference. Figure 8 is a Google Earth image of the area. This testing was performed by C. Petrick and G. Schoep.

4.3.1.1. Test Setup

Testing of bandwidth (BW), received signal strength indication (RSSI) and noise level was performed between two nodes. Tests were conducted with the nodes spaced 370, 540, 990 and 1,090 feet apart. The distances are estimates from Google Earth images (Figure 8). The maximum distance at which the nodes would connect was 1,090. The MeshBoxes were set to 28 mW transmit power and utilized 7dBi gain omnidirectional antennas.

Figure 8: Testing at Montana State University

Node 7 was placed beside the roadway at the top of an eight-foot-tall tripod. The plane of the MeshBox antennas was perpendicular to the direction to Node 8. In other words, the cover of Node 7 was facing Node 8.

Node 8 was in a compact car and had a 7 dBi omnidirectional antenna on a rooftop magnetic mount connected by a six-foot coaxial cable. The rear of the car was pointed toward Node 7 and the antenna was centered on the roof which was approximately four feet above the roadway (Figure 9).

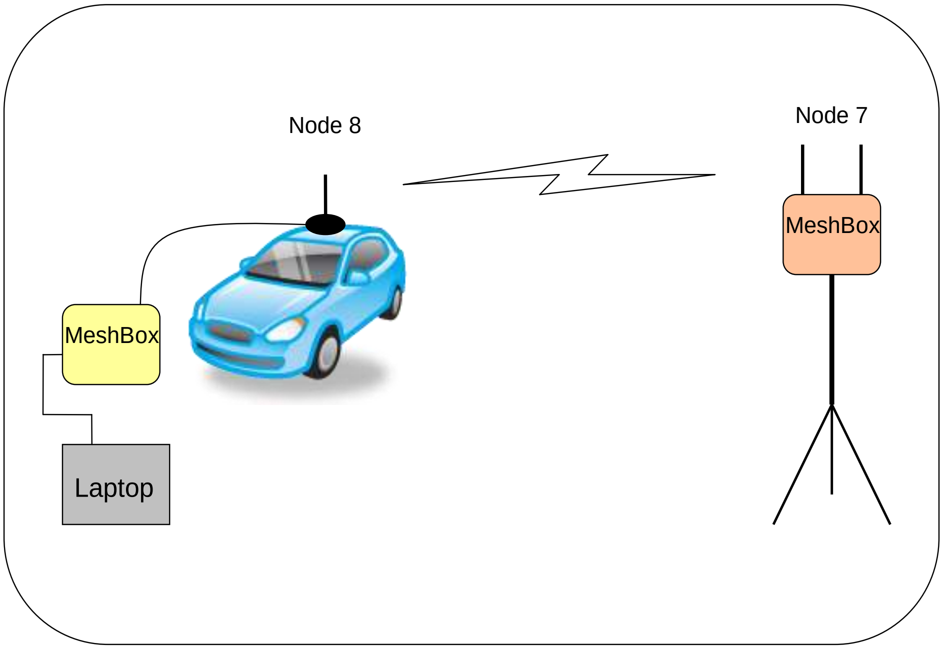


Figure 9: MSU Test Diagram

4.3.1.2. Test Procedure

A laptop was used to log into the MeshBox Freifunk firmware using its local IP address and a web browser. Next, bandwidth tests were performed using the Netperf Bandwidth Measurement application built into the Freifunk firmware. Multiple tests were performed at each site to obtain a more representative measure of the average noise environment.

Note that most wireless routers adjust the link data rate to enable a link, if possible. Thus data rates—i.e., bandwidth—move with the signal-to-noise ratio (SNR); a high SNR enables high data rates and a low SNR produces low data rates.

4.3.1.3. Test Results

Table 5 shows the test results for the 370-foot link on the MSU campus. Note "BW Up" refers to the bandwidth from the car (Node 8) to Node 7, and "BW Down" refers to the bandwidth from Node 7 to Node 8.

Table 5: 370-Foot Link Test Results at MSU

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	8.05	7.50	-78	-93	15
2	7.47	5.63	-78	-88	10
3	8.93	7.17	-79	-92	13
4	7.21	5.88	-77	-90	13
5	9.07	8.07	-79	-91	12
Average	8.15	6.85	-78.2	-90.8	12.6

From the table it can be seen that the BW Up is consistently higher than the BW Down and the SNR is 10 dB or higher.

The test results for the 990-foot link on the MSU campus are shown in

Table 6. The BW Up and Down is 3 to 5 Mbps lower than the 370 foot link and the average SNR is 6 dB lower than the average SNR of Table 5.

The drop in BW is due to lower RSSI, which lowers SNR. SNR must be on the order of 20 dB [11] to enable maximum data rates, so most radios automatically lower their data rates until a link can be established. At a minimum, the RSSI must be slightly higher than the noise for a receiver to see the desired signal, but a link SNR of 1dB will not maintain a link.

Table 6: 990-Foot Link Test Results at MSU

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	2.66	2.68	-87	-92	5
2	2.99	3.18	-87	-92	5
3	3.12	3.08	-85	-93	8
4	2.84	3.11	-86	-94	8
Average	2.9	3.01	-86.25	-92.75	6.5

Table 7 shows the test results for the 1,090-foot MSU link, which was the longest link that could be established. For 1,090 feet the SNR is low, and the BW is well under 1 Mbps and varied significantly.

Table 7: 1,090-Foot Link Test Results at MSU

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	0.54	0.13	-86	-88	2
2	0.41	0.26	-86	-88	2
3	0.98	0.45	-86	-92	6
Average	0.64	0.28	-86	-89.33	3.33

Table 8 shows the test results for the 540-foot link on the MSU campus. Note that in this test the car was moved to the opposite side of Node 7 so the car hood is pointed at the node instead of the trunk. The hood provides a larger ground plane, which will generally improve a mobile antenna's performance. At 540 feet, the BW Down is consistently higher than the BW Up and the SNR is greater than 10 dB, which should provide a consistent link.

Table 8: 540-Foot Link Test Results at MSU

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	8.4	9.0	-81	-95	14
2	8.1	8.5	-81	-95	14
Average	8.25	8.75	-81	-95	14

Table 9 shows the average test results of each parameter for all four link distances. Note that the 540-foot link’s noise level is nearly 3 dB lower than the other link sites. This is possibly due to its location, which was farther away from buildings than the other link sites and in a large empty parking lot. The result is the best SNR and BW of the group despite being approximately 50 percent longer than the 370-foot link.

Table 9: Comparative Link Test Data for MSU

Parameter / Range (ft)	**BW Up (Mbps)**	**BW Down (Mbps)**	**RSSI (dBm)**	**Noise (dBm)**	**SNR (dB)**
370	8.2	6.9	-78.2	-90.8	12.6
540	8.2	8.7	-81.0	-95.0	14.0
990	2.9	3.0	-86.3	-92.8	6.5
1090	0.6	0.3	-86.0	-89.3	3.3

4.3.1.4. Conclusions

The RSSI and SNR values are considerably different than what would be expected from path loss calculations and line-of-sight conditions. Path loss calculations for 2.4 GHz using 7 dBi antennas, 28 mW transmit power, and a receiver threshold of -95 dBm show fade margins—i.e., SNR—of 43.5 dB and 40 dB for 500 and 700 feet, respectively. A 10- to 15-dB difference between measured and calculated would not be unexpected, considering the test equipment used. However 40 dB falls outside the range of what would normally be expected.

Possible causes are radio issues such as inaccurate transmit power, poor antenna performance, or excessive RF cable or connector loss.

4.3.2. Hyalite Canyon, November 2008

On November 6, 2008, testing was done along Hyalite Canyon Road in the Gallatin National Forest south of Bozeman, Montana. This is a typical mountain roadway with frequent changes in elevation and tall evergreen trees lining the right of way (Figure 10). This site was chosen primarily to minimize the likelihood of noise interference. Testing was performed by G. Schoep.

4.3.2.1. Test Setup

Testing bandwidth, RSSI and noise level was performed between two nodes at distances of approximately 525 and 710 feet. The distances are estimated from Google Earth images. At the location chosen, 710 feet was the maximum distance the nodes would connect. The nodes were set to 75 mW output and had 7 dBi gain omnidirectional antennas attached.

Figure 10: Test Locations in Hyalite Canyon, MT

Node 6 was placed on an embankment approximately 20 feet from the roadway on an eight-foot-tall tripod that was approximately six feet above the roadway, putting it about 14 feet above the roadway.

Node 8 was in a full-size pickup truck and had a 7 dBi omnidirectional antenna on a rooftop magnetic mount connected by a six-foot coaxial cable. The pickup was pointed toward Node 6 for both tests and the antenna was located on the passenger side of the roof, approximately five feet above the roadway.

4.3.2.2. Test Procedure

The laptop was used to log into Node 8 Freifunk firmware using its local IP address and a web browser. Next, BW tests were performed using the Netperf Bandwidth Measurement application built into the Freifunk firmware. Multiple tests were performed at each site to obtain a better representation of the average noise environment.

4.3.2.3. Test Results

A number of hardware and software problems caused challenges in testing. Nearly two hours were spent debugging the setup before testing could begin. The initial link setup distance was approximately 150 feet but a link could not be established. It was found that one radio's operating channel had been changed unknowingly, another radio was not working at all, another radio's batteries were dead by the time the problem with the first radio was found, and the Node 8 radio did not select the antenna automatically although the firmware was set to automatic. The antenna port in the firmware had to be manually selected to get Node 8 to work properly.

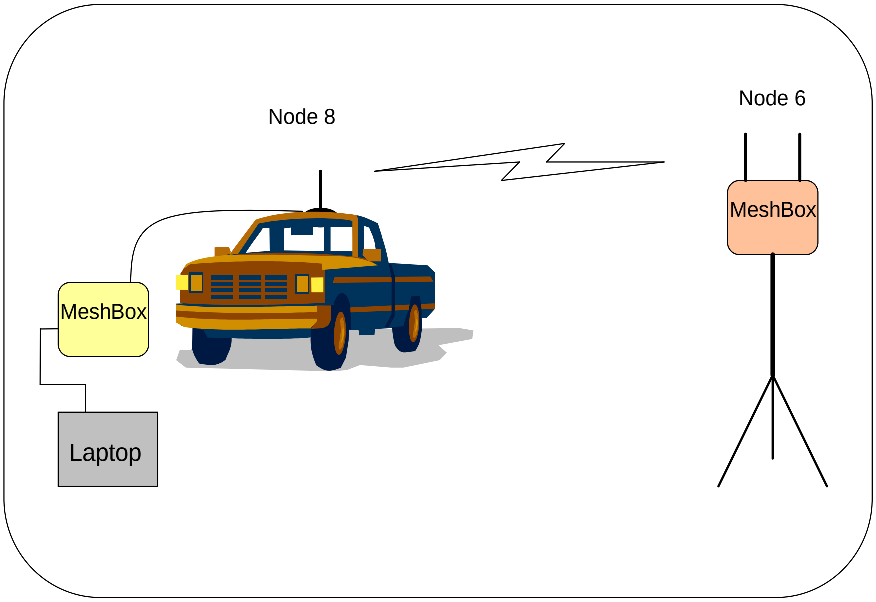


Figure 11: Hyalite Canyon Test Diagram

Test results shown in Table 10 indicate that radio noise in the forest was low and consistent. They also show the BW Up is consistently higher than the BW Down, which may be due to a radio problem or that the elevation difference in the antennas was having an adverse effect.

Note that RSSI and noise measurements from a router are not expected to be highly accurate—the router is not a test instrument—but these measurements are useful for comparative purposes.

Table 10: BW Tests in Hyalite Canyon at 535 Feet

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	6.02	3.74	-89	-96	7
2	5.75	3.12	-90	-96	6
3	6.06	3.81	-92	-96	4
4	2.26	1.72	-91	-96	5
5	2.76	1.94	-91	-95	4
Average	4.57	2.87	-90.6	-95.8	5.2

Table 11 again shows the effect of a lower SNR on BW. Although this was the farthest apart the radios would link, the SNR values were comparable to those for the 535-foot test.

Table 11: BW Tests in Hyalite Canyon at 710 Feet

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	2.34	1.69	-93	-97	4
2	3.58	2.23	-93	-97	4
3	4.63	2.12	-91	-97	6
4	2.64	1.72	-93	-96	3
Average	3.3	1.94	-92.5	-96.75	4.25

The RSSI and SNR values are considerably different than would be expected from path loss calculations and line-of-sight conditions. Path loss calculations for 2.4 GHz using 7 dBi antennas, 75 mW transmit power, and a receiver threshold of -95 dBm show fade margins (SNR) of 43.5 dB and 40 dB for 500 and 700 feet, respectively. A 10 to 15 dB difference between measured and calculated would not be unusual, but these results show a 40 dB difference.

Possible causes are radio issues or multipath interference. Multipath interference occurs when a signal travels two or more paths to a receiver thus arriving out-of-phase with one other. The paths are typically a direct path and a reflected path. The effect of multipath is destructive interference or fading of the signal. Multipath interference over this short of distance especially in the forest would be unlikely so it's most likely an issue with the radios. Possible radio problems include inaccurate transmit power, poor antenna performance, excessive RF cable or connector loss.

4.3.3. Adjacent to WTI, October 2009

On September 28, October 1, and October 2, 2009, further testing was done in a field near the WTI offices. The field is flat with no obstacles or vegetation between router and node (Figure 12). This testing was performed by R. Parker, an undergraduate student research assistant.

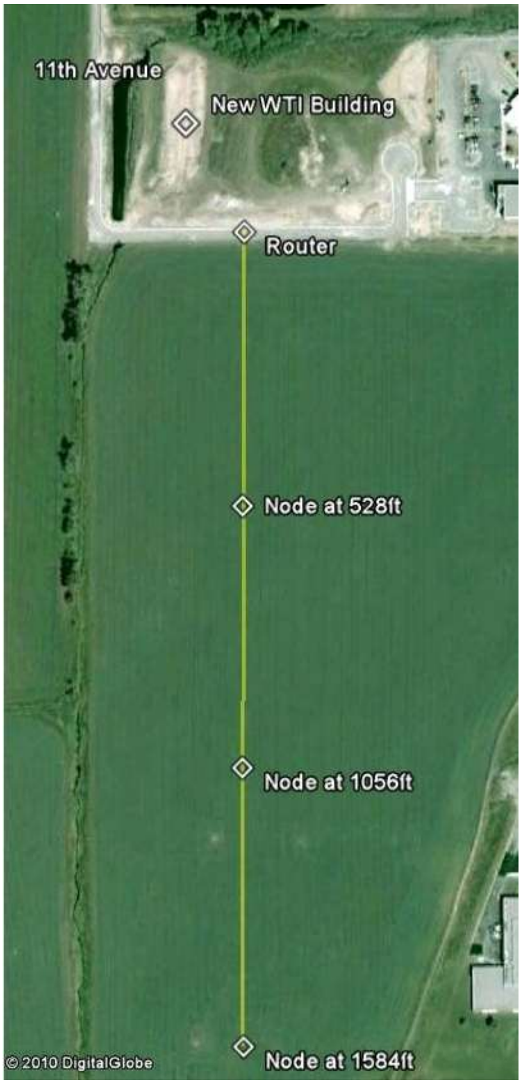


Figure 12: Test Locations near the WTI Facility

4.3.3.1. Test Setup

The node and router were set up at a height of six feet, and facing each other at distances of 528 feet, 1,056 feet, and 1,584 feet (Figure 13). The router's transmit power was set to 28mW and node transmit power was set to 75mW, which are the default values for each device. Note that in later testing at the 27th Avenue site, Node 10's transmit power was set to 75mW for comparison purposes.

Both the router and nodes were powered by an external 12-volt battery. The router was connected to the laptop via a category 5 (Cat 5) Ethernet cable. The laptop was located approximately 20 ft behind the router to minimize any interference coming from the test equipment or tester.

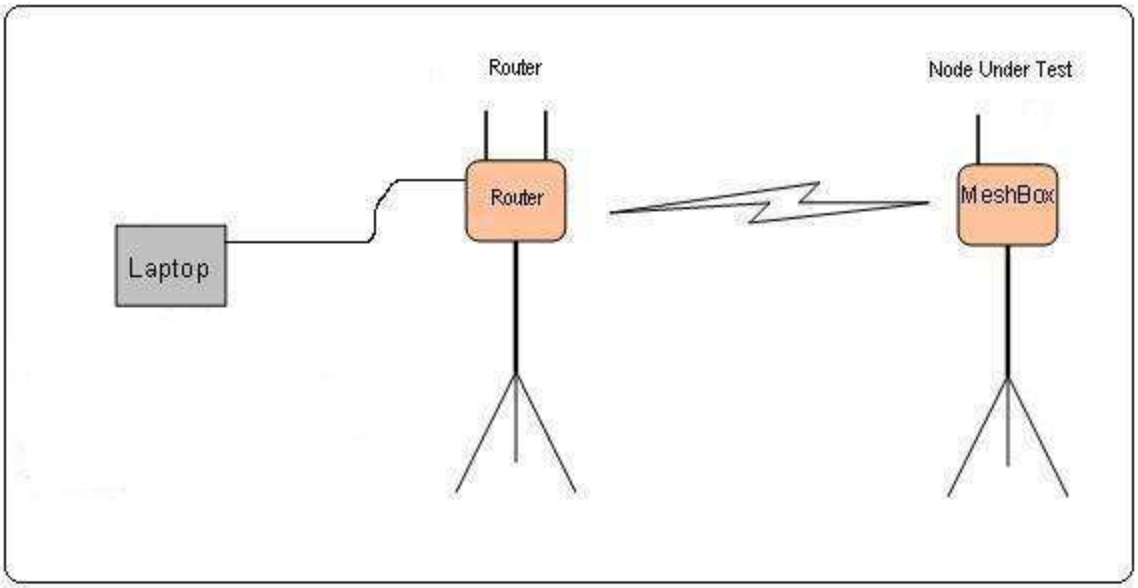


Figure 13: WTI Test Setup Diagram

4.3.3.2. Test Procedure

The laptop was used to log into the DD-WRT firmware installed on the router and monitor router performance. By running the Site Survey test within DD-WRT, RSSI and Noise were obtained from the node and recorded. Since WiFi noise levels can be very dynamic, the Site Survey tests were run approximately one minute apart for a total of 10 trials. This provided a reasonable average noise level without requiring an inordinate amount of test time. To minimize potential problems, only one antenna was installed on the test node's B channel; channel A was disabled through the firmware and channel B was selected as both the transmit and receive channel.

It was decided to perform the tests in steps of one-tenth of a mile: 528 feet, 1,056 feet and 1,584 feet. Mainly due to the test area chosen, 1,584 feet was the longest range that could be tested. For comparison purposes two antennas and two nodes were tested at each range. Based on prior performance, antennas 12 and 17 and Nodes 7 and 10 were selected for testing. Ten tests were performed with antenna no. 12, then the antenna was changed and another ten tests were performed using antenna no. 17. Testing began at the 528-foot range and all tests were completed before moving to the next range. The order of testing was maintained for all tests at the location—i.e., if Node 10 was tested first at 528 feet, it was also tested first at 1,056 feet and at 1,584 feet.

4.3.3.3. Test Results

RSSI and noise measurements using a router are not test-instrument accurate but are useful for comparative purposes. Raw test data, in table form, is available in the appendix. Note the power values in the tables are in dBm. Decibel (dB) is a power ratio and dBm is the power value referenced to one milliwatt. A change from one milliwatt to two milliwatts is a 3 dB change.

4.3.3.3.1. Node 7 Tests

528-Foot Link Distance

Table 12 shows the difference in performance between antennas 12 and 17. The results show antenna no. 17 received twice as much power for both RSSI and Noise as no. 12, allowing for better performance.

Table 12: Antenna Performance Comparison for 528 Feet

Parameter / Antenna No.	Average RSSI (dBm)	Average Noise (dBm)	Average SNR (dB)
12	-72	-92.5	20.5
17	-68.9	-89.3	20.4
17 – 12 (dB)	3.1	3.2	-0.1

This conclusion is contradicted by the data taken at the next link distance, 1,056 feet. The difference could be due to antenna quality, a connector issue, or a change in internal node performance. Antenna quality issues could be differences in construction or internal damage to the antenna. Connector issues could be due to the antenna connector not completely engaged (screwed on) when making the measurements. A change in node performance could be caused by the node’s connector being damaged when the antenna was changed.

1,056-Foot Link Distance

The node spacing was increased to 1,056 feet and another data set was taken for both antennas. Table 13 shows the performance difference between antennas 12 and 17 at this distance. In this data set, antenna 12 performs slightly better than antenna 17.

Table 13: Antenna Performance Comparison for 1056 Feet

Parameter / Antenna No.	Average RSSI (dBm)	Average Noise (dBm)	Average SNR (dB)
12	-76.4	-91.7	15.3
17	-77.6	-93.6	16
17 – 12 (dB)	-1.2	-1.9	0.7

.

1,584-Foot Link Distance

The node spacing was increased to 1,584 feet and the tests repeated. Table 14 shows the difference between antennas 12 and 17 at 1,584 feet. Antenna no. 17 again appears to be a slightly better antenna.

Table 14: Antenna Performance Comparison for 1584 Feet

Parameter / Antenna No.	Average RSSI (dBm)	Average Noise (dBm)	Average SNR (dB)
12	-85.0	-91.0	6.0
17	-83.7	-90.5	6.8
17 – 12 (dB)	1.3	0.5	0.8

Discussion

The values shown in Table 12 are typical test results one would expect to see when checking for a bad antenna. In other words, the RSSI and noise value difference between antennas should be approximately the same since both are obtained from the same receiver. One would expect RSSI to be consistent for all ten measurements due to the fact that the transmit power is constant and the transmitter is stationary. Noise on the other hand is expected to be more inconsistent due to the many and variable sources causing it, so the Noise results in Table 14 are surprisingly consistent. Also, a bad antenna's SNR would be the same as a good antenna's due to the fact that SNR is the difference between two received values. If an antenna's performance is poor, it will be poor for both RSSI and noise measurements so the SNR difference will be the same as a good antenna.

Table 15 shows the RSSI, Noise, and SNR change, if any, due to a link distance change. They are calculated from the values found in Tables 35-37 in the appendix. For example, the antenna no. 12 RSSI Diff. in dB for 1,056 feet–528 feet (-4.4) equals the average RSSI for antenna no. 12 in

Table 36 (-76.4) minus the average RSSI for antenna no 12 in Table 35 (-72).

Table 15: Signal Level Change with Link Distance

Parameter / Links	Antenna No. 12			Antenna No. 17		
	RSSI Diff. (dB)	Noise Diff. (dB)	SNR Diff. (dB)	RSSI Diff. (dB)	Noise Diff. (dB)	SNR Diff. (dB)
1,056' – 528'	-4.4	0.8	-5.2	-8.7	-4.3	-4.4
1,584' – 1,056'	-9.6	0.7	-9.3	-6.1	3.1	-9.2
1,584' – 528'	-13	1.5	-14.5	-14.8	-0.8	-13.6

As expected, RSSI diminishes with increased distance for antenna 12, as does SNR. Since noise level is not a function of range, one would expect it to remain relatively constant as shown. Theoretically there is a 6dB increase in free space path loss or a 6dB reduction in signal strength when the link distance is doubled. That does not occur in the antenna 17 RSSI results, which makes the results suspect and suggest there was an error in testing somewhere.

The noise values for antenna 12 are what one would expect for a rural environment, relatively constant, whereas the noise values for antenna 17 are not. That could be explained by testing errors or an interference source in or near the WTI office building. The test location would be moving away from the interference source as the test range increased, therefore becoming weaker.

4.3.3.3.2. Node 10 Tests

Antenna tests with Node 10 were performed within an hour of Node 7 tests. Table 16 shows a performance comparison between antennas 12 and 17 at the 528-foot range.

Table 16: Antenna Performance Comparison at 528 Feet

Parameter / Antenna No.	Average RSSI (dBm)	Average Noise (dBm)	Average SNR (dB)
12	-62.8	-91.1	28.3
17	-64.6	-91.9	27.3
17 – 12 (dB)	-1.8	-0.8	-1.0

Table 17 shows the average test results for antennas 12 and 17 at the 1,056-foot range. The test data shows antenna no. 12 is better than antenna no. 17, since no. 12 received over twice as much power, 3 dB, as did no. 17. This points to testing errors as it is a direct contradiction to the results in Table 12.

Table 17: Antenna Performance Comparison at 1,056 Feet

Parameter / Antenna No.	Average RSSI (dBm)	Average Noise (dBm)	Average SNR (dB)
12	-68.6	-91.0	22.4
17	-72.3	-91.1	18.8
17 – 12 (dB)	-3.7	-0.1	-3.6

The node spacing was increased to 1,584 feet and another data set was started, however a substantial increase in RSSI (40dB) occurred after the third test (Table 40). The 40dB increase in RSSI results continued after changing antennas from no. 17 to no. 12. The first three test results were similar to the Node 7 test results at 1,584 feet. Nothing in the test setup was knowingly changed that could explain this dramatic change in RSSI. Since RSSI was the only tested parameter to change, either Node 10 suddenly increased output power by a factor of 10,000 or something in the router suddenly changed. The nodes had been set at the maximum power allowed by the software so increasing transmit power by 40dB is unlikely. The logical conclusion is something temporarily changed in the router since further testing with the same router has produced results similar to results recorded before the anomaly. See sections 4.1.4 and

4.1.5. Testing for both Node 7 and Node 10 at 1,584 feet was done on the same day at the same location within an hour of each other.

Table 18 shows a performance comparison for antennas 12 and 17 at the 1,584-foot range. For this data set, antenna no. 12 performed slightly better than antenna 17 although the difference is within measurement error.

Table 18: Antenna Performance Comparison at 1,584 Feet

Parameter / Antenna No.	Average RSSI (dBm)	Average Noise (dBm)	Average SNR (dB)
12	-44.7	-91.5	46.8
17	-45.7	-91.9	46.2
17 – 12 (dB)	-1.0	-0.4	-0.6

The RSSI and SNR values are considerably different than those found for Node 7 at 1,584 feet. When testing with antenna no. 17, the initial three values were very similar to those recorded with Node 7. However after the first three tests, the SNR increased dramatically due to a large gain in RSSI. This improved SNR continued when the antenna was changed from no. 17 to no. 12. When the antenna was swapped, it was noticed that the Type N panel-mount adaptor on channel B of Node 10 was loose. After testing was finished no other discrepancies were found. No further data at this distance was taken due to bad weather and loss of field use. Further testing at 1,584 ft was attempted at the 27th Avenue location (Figure 16) but the area had too much radio interference to enable a link so no further data was taken.

Table 19 shows the RSSI, Noise, and SNR changes due to link distance change for Node 10. Due to the 40dB shift in RSSI for the 1,584-foot measurements, the table is not especially useful but is presented for completeness.

Table 19: Signal Level Change with Link Distances for Node 10

Parameter / Links	Antenna No. 12			Antenna No. 17		
	RSSI Diff. (dB)	Noise Diff. (dB)	SNR Diff. (dB)	RSSI Diff. (dB)	Noise Diff. (dB)	SNR Diff. (dB)
1056' – 528'	-5.8	0.1	-5.9	-7.7	0.8	-8.5
1584' – 1056'	23.9	-0.5	24.4	26.6	-0.8	27.4
1584' – 528'	18.1	-0.4	18.5	18.9	0.0	18.9

Replacing the router with Node 10 in Figure 13, BW measurements were performed. Table 20 shows the BW measurement results for the 528-foot range. Both nodes transmit power was set at 75 mW. Node 10 was the base station node and node 7 is the relay node. Freifunk firmware was used to test the bandwidth. The testing was done at the same time as the previous 528-foot SNR tests.

Table 20: BW Test Results for a 528-foot Link between Node 7 and 10.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	Diff. BW Down – UP (%)
1	7.64	8.76	14.7
2	7.57	8.84	16.8
3	7.67	9.78	27.5
4	8.53	9.96	16.8
5	7.5	8.64	15.2
Average	7.78	9.2	18.3

The consistent difference between BW Down and BW Up may be due to the bandwidth allocation settings in the Freifunk firmware or a difference in local noise. With SNR over 20 dB there would not be any environmental reason for the difference in Up/Down rates.

Averaging the RSSI and Noise data for all nodes and all antennas shows typical results (Table 21). That is, RSSI decreases approximately 6 dB and Noise stays about the same when the link distance doubled.

Table 21: Average Total SNR Testing at WTI

Test	RSSI (dBm)	Noise (dBm)	SNR (dB)
Average 528 ft (All Nodes, All Antennas)	-67.1	-91.2	24.1
Average 1,056 ft (All Nodes, All Antennas)	-73.7	-91.9	18.1

4.3.3.4. Conclusions for WTI Testing

Since most of the antenna data is contradictory and inconsistent, no antenna conclusions can be drawn. If the data from Node 10 at 1,584 feet is disregarded, the results look like one would expect. However, given the anomalous results with Node 10 at 1,584 feet and the poor performance of Node 7 at 1,584 feet, it appears 1,584 feet is at or exceeds the maximum distance for reliable communication at least for these conditions.

4.3.4. Durston Avenue, October 2009

Further MeshBox testing was performed on October 15, 2009, at the intersection of Durston and Cottonwood Avenues in Bozeman, MT. This is a soccer field complex that is level. The testing was performed in the empty parking lot. Unfortunately, the complex measures only 1,056 feet from corner to corner and at testing time the fields were still in occasional use, so testing could only be done at 528 feet (Figure 14). Testing was performed by R. Parker.

Figure 14: Test Setup at Durston Ave Facility

4.3.4.1. Testing Setup

The MeshBox and router were setup at a height of six feet, and faced each other at a distance of 528 feet (Figure 15). Router transmit power was set at maximum, 28mW, and the MeshBox transmit power was set at 75mW. One antenna, no. 17, was used to test the MeshBoxes and was installed on channel B. Both the router and MeshBox were powered by external batteries. The laptop was connected to the router with a Cat5 cable and used to monitor the link performance via the router's DD-WRT firmware. The laptop was placed approximately 20 feet behind the router to minimize any possible interference from the test equipment or tester. A total of three MeshBoxes/nodes were tested at this location—Node 6, Node 9 and Node 11.

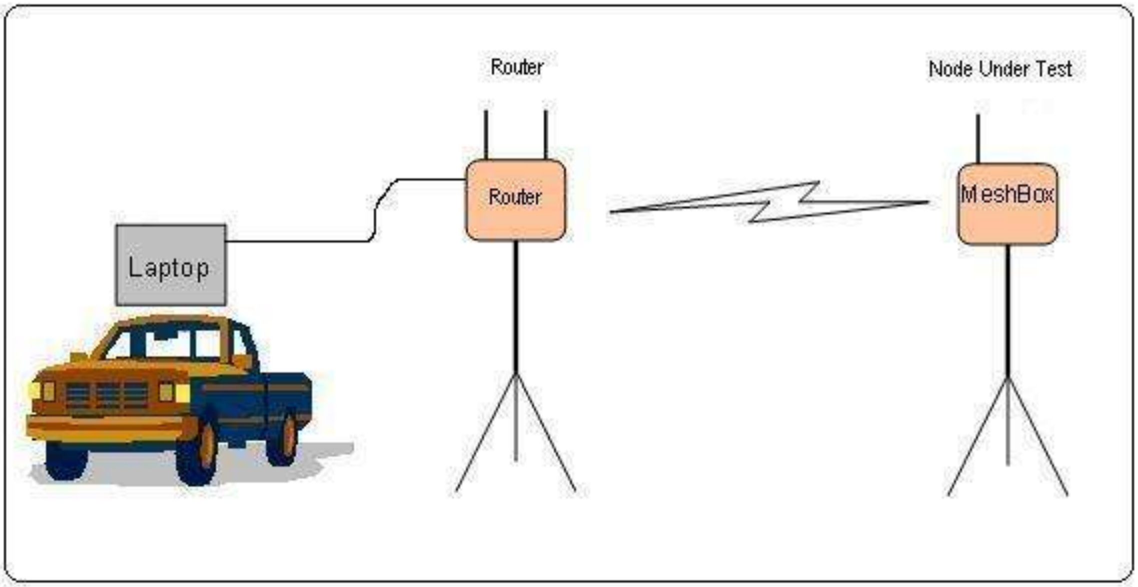


Figure 15: Durston Avenue Test Diagram

4.3.4.2. Test Procedure

The laptop was utilized for logging into the router's DD-WRT firmware and to monitor the routers performance. By running the Site Survey test within DD-WRT, RSSI was obtained from the node and noise level was obtained at the router and recorded. Since WiFi noise levels can be very dynamic, the Site Survey tests were run approximately one minute apart for a total of 10 trials. This provided a reasonable average noise level without spending an inordinate amount of time testing. Similar to the previous testing, only one antenna was installed on the test node's B channel; channel B was selected as both the transmitting and receiving channel through the firmware. Channel A was not enabled.

4.3.4.3. Test Results

Table 22 shows the averaged test results for Nodes 6, 9, and 11. The results for the three nodes are averaged for comparison with results from other locations. The raw test data is available in appendix Table 41, Table 42, and Table 43.

From the table it can be seen that the three nodes showed similar performance with an average RSSI in the lower negative sixties.

Table 22: Durston 528-foot Test Results Comparison Table

Parameter / Node No.	RSSI (dBm)	Noise (dBm)	SNR (dB)
6	-61.8	-88.9	27.1
9	-63.1	-86.2	23.1
11	-61.9	-87.4	25.5
Average	- 62.3	- 87.5	25.2

Table 23 shows the results for all nodes tested at 528 feet. It illustrates that Node 7 is a poor performing node.

Table 23: Test Results Comparison for 528 Feet at WTI and Durston Avenue

Parameter / Location	Node	RSSI (dBm)	Noise (dBm)	SNR (dB)
WTI	7	‘-68.9	‘-89.3	‘20.4
	10	-64.6	-91.9	27.3
Durston	6	-61.8	-88.9	27.1
	9	-63.1	-86.2	23.1
	11	-61.9	-87.4	25.5
Average (w/o 7)	-	- 62.9	- 88.6	25.8

4.3.5. 27th Avenue, Winter 2009

In December 2009 and January and February 2010, testing was done on 27th Avenue between Baxter Avenue and Oak Street in Bozeman. This area is mostly flat, especially where testing was done along the sidewalk. Use of the sidewalk allowed researchers to avoid most obstacles such as trees and large changes in elevation (Figure 16). Small trees did line the sidewalk, though there were none directly between the two MeshBoxes. Though there was room to test up to 0.3 miles (1,584 ft), there was wireless activity in this area that caused more noise (refer to section 4.3.3). As a result, no reliable communications links could be made at 0.3 miles (1,584 ft). This testing was performed by R. Parker.

4.3.5.1. Test Setup

Both MeshBoxes were set up at a height of six feet and faced each other at distances of 528 feet and 1,056 feet (Figure 17). Transmit power was set at 75 mW for both MeshBoxes. Base station MeshBox used one antenna, no. 12, connected to channel B. Relay station MeshBox also used one antenna, no. 17, connected to channel B. Both MeshBoxes used external battery power. The base station was connected to a laptop via Cat5 cable. The laptop monitored communication with Freifunk software installed on both MeshBoxes. The laptop was placed approximately 20 feet behind the base station to minimize any interference from the test equipment or the tester.

Figure 16: Testing at 27th Avenue site, Bozeman, MT

4.3.5.2. Test Procedure

Bandwidth was measured, followed by RSSI and Noise a few seconds later. A few measurements show a discrepancy between measured BW and SNR, i.e., a high BW but a low SNR. This is probably due to the measurements not being concurrent. Each measurement was taken approximately one minute apart.

4.3.5.3. Test Results

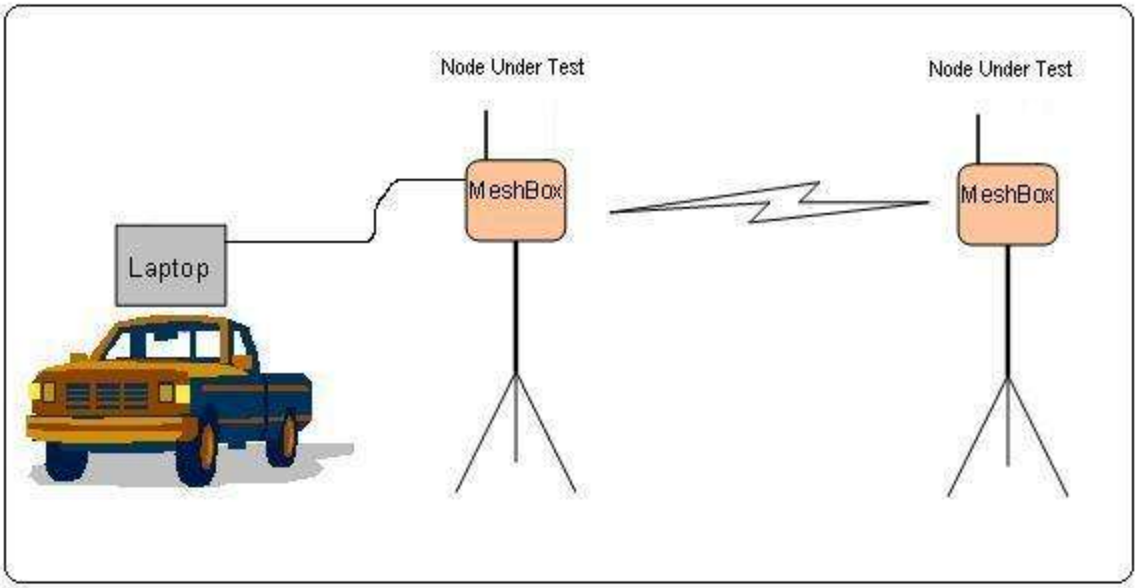


Figure 17: 27th Avenue Test Diagram

Two rounds of testing were done with Node 10 as the base station node. Node 7 was the relay station node and was placed at 528 feet and then 1,056 feet. Both nodes were placed on top of six-foot tripods and powered from external 12V batteries. Both MeshBoxes were set to transmit at 75 mW power level. The RSSI and Noise levels were measured a few seconds after BW; consequently SNR and BW data may not correlate (normally the higher the SNR, the higher the BW).

Table 24 shows the averaged test results at 528 feet and 1,056 feet, respectively, for Nodes 10 (base) and 7 (relay). Ten tests were performed at each distance. The raw test data is available in appendix Table 44 and Table 45.

Table 24: Link Performance vs. Distance – Nodes 10 and 7

Distance \ Parameter	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
528 Feet	5.5	6.5	-69.8	-86.4	16.6
1,056 Feet	0.2	1.7	-78.7	-87.1	8.4

Table 25 is the averaged test results at 528 ft for multiple nodes, each tested separately, with Node 5 acting as base station. Five measurements were taken for each node under test in order to assure each node was tested in the time available. Note Node 5 was arbitrarily chosen as the base and the raw test data is available in appendix Tables 46 – 53.

Table 25: Node Average Performance Comparison Table for 528 Feet

Parameter / Node #	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
2	3.1	2.1	-64.6	-84.0	19.4
3	2.4	1.7	-64.4	-79.6	15.2
6	2.0	1.9	-64.8	-84.6	19.8
7	3.6	2.5	-73.4	-89.4	16.0
8	3.3	2.7	-73.2	-91.8	18.6
9	2.4	1.4	-71.0	-86.2	15.2
10	3.6	2.2	-64.0	-86.2	22.2
11	3.4	1.8	-65.4	-84.8	19.4
Average	3.0	2.0	- 67.6	- 85.8	18.2

Table 26 shows the average aggregate test data at 528 feet for the 27th Avenue test site. The SNR was ~7 dB less than the measured values at the Durston test site and ~6 dB less than that measured at the WTI test site. This test site did have more wireless activity than the other test sites and as a result the average noise floor at 27th Avenue was 2 to 5 dBm higher than either the Durston and WTI sites. Average BW compares well to testing done at 990 feet at WTI with power set at 28mW. However the SNR was much lower for 28mW Tx power than for 75mW Tx power at any site. The lowest average SNR at 75 mW for 528 feet is 18.4 dB at the 27th Avenue site. The highest SNR for 28 mW transmit power was 14 dB at WTI at 540 feet.

Table 26: Average Total SNR and BW Testing at 27th Ave at 528 Feet.

Parameter	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
Average (All Nodes)	3.26	2.53	-67.84	-85.89	18.4

Table 27 shows test results for the 27th Avenue test site at 1,056 feet. Nodes 10 and 11 were chosen based on the test results taken at 528 feet (Table 25). Both nodes had SNRs near 20 dB. Node 10 was used as the base and Node 11 the relay node.

Table 27: SNR and BW Test Results for 27th Avenue at 1,056 Feet. Base–Node 10, Relay–Node 11.

Parameter / Test	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
Average	2.7	1.4	-74.8	-87.3	12.5

Table 28 shows the average aggregate test data for 27th Avenue at 1,056 feet. The SNR measured here was ~8 dB lower than that measured at WTI for the 1,056-foot link. Average BW is less than half that measured at 528 feet at this same location.

Table 28: All Node Total SNR and BW Testing at 27th Avenue at 1,056 Feet.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
All Nodes	1.42	1.52	-76.75	-87.20	10.45

Table 29 shows testing results at 27th Avenue at 1,056 feet using a router; transmit power was set at 75 mW. The node under test is Node 10 and its Tx power is also set at 75 mW. This test was done as a comparison to the node-to-node tests done at 75 mW since all other tests with a router were with the router set to 28 mW transmit power level. Comparing the RSSI in Table 29 to the RSSI in Table 27 above, the router performance is similar to Node 10. Note that the comparison between router and node would have been more accurate if Node 11 had been used instead of Node 10. Node 11 was the node being tested in Table 27 but Node 10 was the node tested in Table 29.

Table 29: Router Test Results at 27th Avenue at 1,056 Feet. Node 10.

Parameter / Test	RSSI (dBm)	Noise (dBm)	SNR (dB)
Average	-72.8	-84.6	11.8

Figure 18 is a line graph of the average RSSI, Noise and SNR measured at 27th Avenue for distances of 528 feet and 1,056 feet. It shows that the signal strength (RSSI) decreased with distance and noise stayed (relatively) constant, which caused the SNR to decrease.

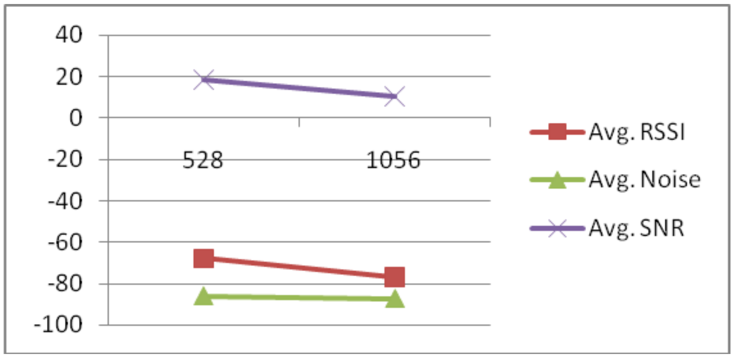


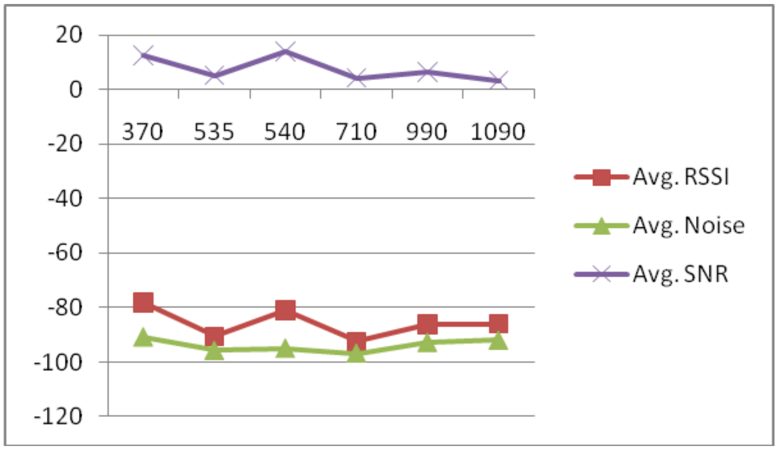
Figure 18: Link Performance vs. Distance (27th Avenue)

Table 30 shows the averaged measured values for each test location and link distance. It is presented for informational purposes only since direct performance comparisons generally cannot be made due to variation in the transmit power settings. Some measurements were made with 28mW transmit power and others were made with 75 mW transmit power.

Table 30: Averaged Link Test Results vs. Distance

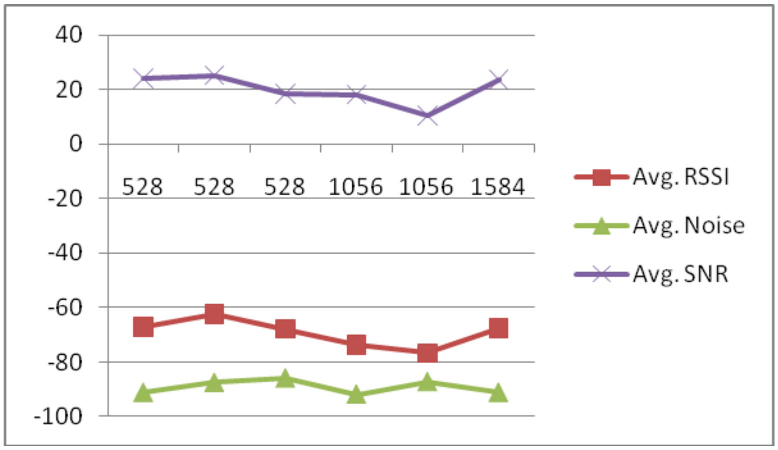
Parameter / Distance (ft)	Avg. BW Up (Mbps)	Avg. BW Down (Mbps)	Avg. RSSI (dBm)	Avg. Noise (dBm)	Avg. SNR (dB)
WTI					
370	8.2	6.9	-78.2	-90.8	12.6
528	7.8	9.2	-67.1	-91.2	24.1
540	8.2	8.7	-81.0	-95	14
990	2.9	3.0	-86.3	-92.8	6.5
1,056	NA	NA	-73.7	-91.9	18.1
1,090	0.6	0.3	-86.0	-92	3.3
1,584	NA	NA	-67.7	-91.2	23.5
Durston					
528	NA	NA	-62.3	-87.5	25.2
27th Ave					
528	3.3	2.5	-67.8	-85.9	18.4
1,056	1.4	1.5	-76.8	-87.2	10.5
Hyalite					
535	4.6	2.9	-90.6	-95.8	5.2
710	3.3	1.94	-92.5	-96.8	4.3

Figures 19, 20, 21 and 22 are visual representations of the measured data in Table 30. Again, one would expect the RSSI to linearly decrease with link distance, and the noise to vary with location and time (hour, day, and week). Since the measurements were made at many locations with many different combinations of nodes, it is difficult to come to any definite conclusions about node performance. Generally the figures show the measurement variability that results from wireless testing at different locations without careful control of the test equipment and setups.



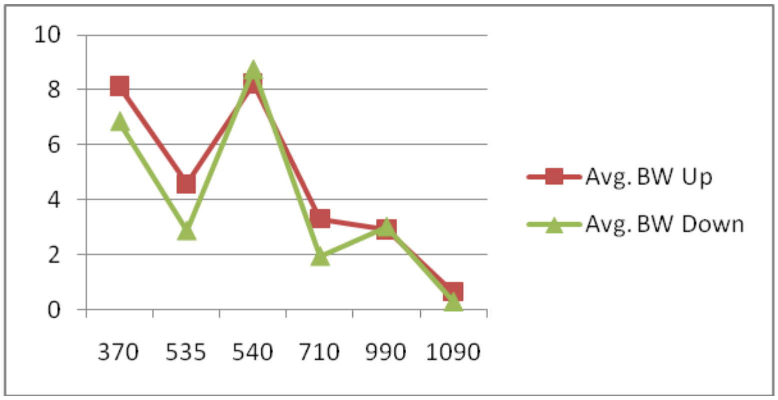
WTI Hyalite WTI Hyalite WTI WTI

Figure 19: Link Performance vs. Distance (28 mW)



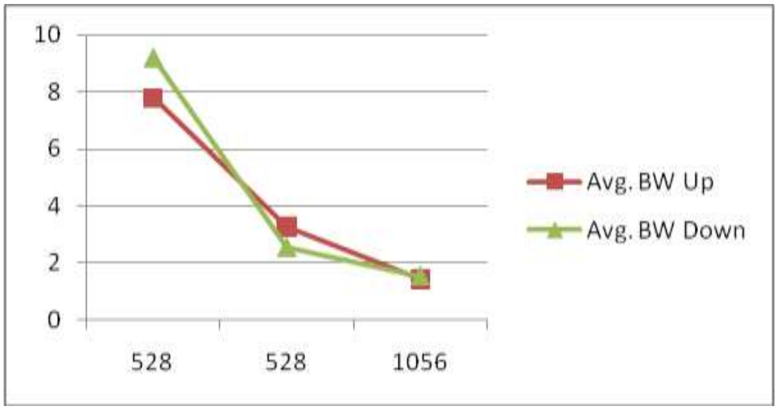
WTI Durston 27th WTI 27th WTI

Figure 20: Link Performance vs. Distance (75 mW)



WTI Hyalite WTI Hyalite WTI WTI

Figure 21: BW vs Distance (28 mW)



WTI 27th 27th

Figure 22: BW vs Distance (75 mW)

4.4. Wi-Fi Wireless Surveys for WTI, Durston and 27th Avenue Test Sites

A Wi-Spy 2.4i spectrum analyzer was used to survey the interference levels at the WTI, Durston and 27th Avenue test sites. Since the survey was completed several months to a year after node testing ended, the results may not be indicative of the interference levels during node testing, but the results do provide a point of comparison.

Figure 23 displays the plotted signal power in dBm versus the Wi-Fi channel at the WTI location for a 15-minute time period. The top view has the amplitude of each signal plotted at each frequency for the 15-minute period. In the top view, the brighter the color (red) the more signal power, i.e., interference is present. The top view can be utilized for determining the type of interferer, e.g., Uniden phone, soundcast, wireless video device, etc.

The bottom view shows the average power level in dBm at each frequency in green and the maximum power level in blue. The bottom view was used for creation of the following tables.

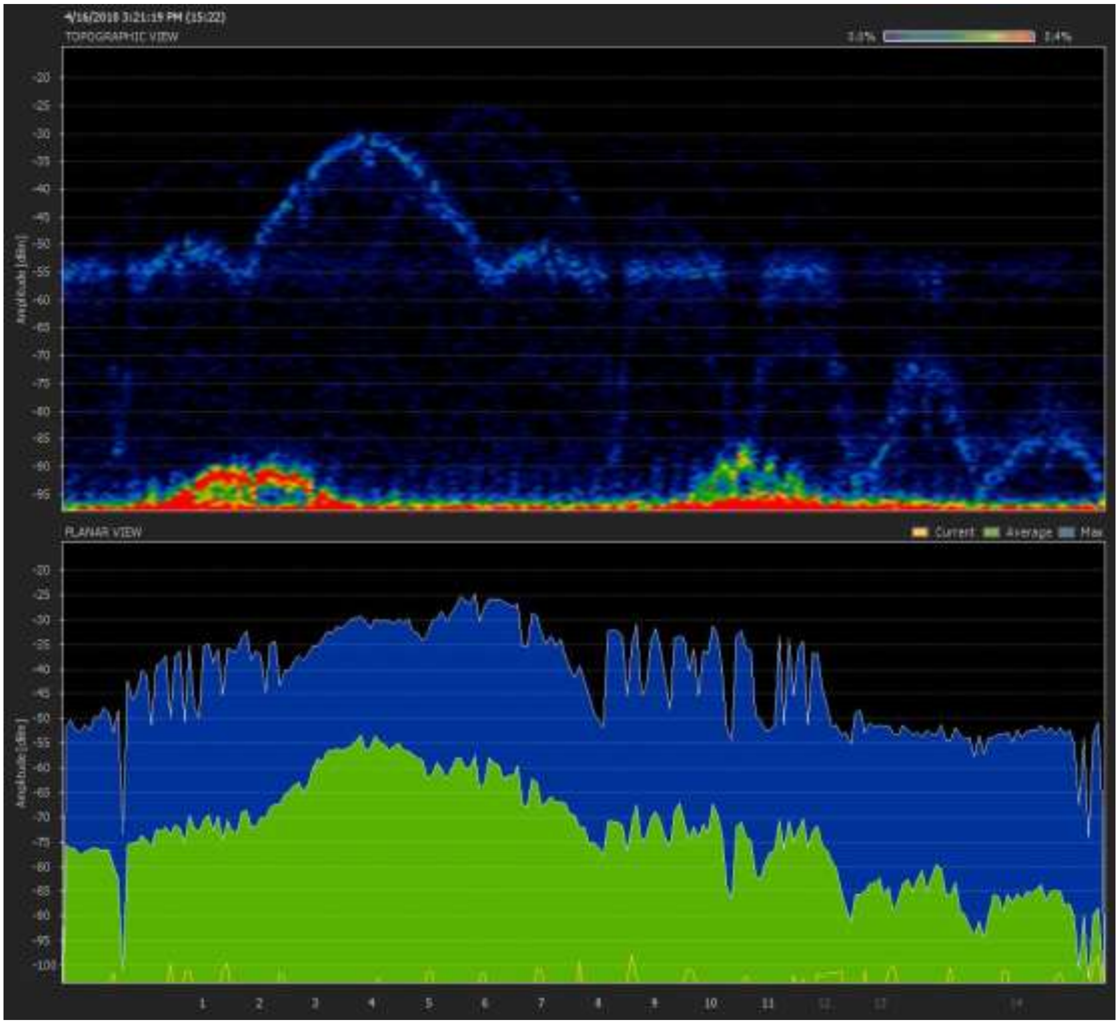


Figure 23: Chanalyzer 3.4 Interference Plots for WTI Location

4.4.1. WTI Wi-Fi Spectrum Survey

Table 31 shows the duty cycle, average and maximum signal levels across all Wi-Fi channels in the 2.4 GHz wireless range for the WTI test site. Data was collected using a MetaGeek Wi-Spy spectrum analyzer and Chanalyzer software in April of 2010. The software grades the channels for new communication device use, with "A" being the best.

According to MetaGeek, the Channel Table Grade "is a weight for each frequency/amplitude point based on how close it is to the center of the channel and its amplitude." It's a measure of the RF noise occurring within the channel. Duty Cycle is a relative score based on how much RF activity is in the channel in the specified time range and is weighted so the center channel frequencies produce higher scores.

The -25 dBm signal is a strong signal level and indicates the interferer was in close proximity to the tester, but the low duty cycle indicates the interfering signal was not present often.

Channels 12 and 13 are not legal Wi-Fi channels in the United States, but are included for completeness.

Table 31: Wi-Fi Wireless Survey for WTI (MSU).

Wi-Fi Channel	Grade	Duty Cycle %	Average (dBm)	Max (dBm)
1	98 (A)	0.12	-67.88	-32.5
2	98 (A)	0.25	-61.02	-29.5
3	98 (A)	0.25	-59.21	-29.5
4	98 (A)	0.16	-58.48	-25
5	98 (A)	0.14	-58.33	-25
6	98 (A)	0.11	-59.43	-25
7	98 (A)	0.06	-62.82	-25
8	98 (A)	0.04	-65.41	-25
9	98 (A)	0.03	-70.2	-29
10	98 (A)	0.03	-72.54	-31
11	99 (A)	0.03	-73.67	-31.5
12	99 (A)	0.03	-75.71	-31.5
13	99 (A)	0.03	-78.42	-33.5

4.4.2. Durston Wi-Fi Spectrum Survey

Table 32 shows the duty cycle, average and maximum signal levels across all channels in the 2.4 GHz wireless range for the Durston Avenue test site. Data was collected using a Wi-Spy spectrum analyzer and Chanalyzer software in April of 2010. Again the software grades the channels for new communication link use, with "A" being the best.

Table 32: Wi-Fi Wireless Survey for Durston Avenue.

Wi-Fi Channel	Grade	Duty Cycle %	Average (dBm)	Max (dBm)
1	100 (A)	0.01	-76.5	-31.5
2	100 (A)	0.01	-75.02	-30.5
3	100 (A)	0.01	-73.03	-29
4	99 (A)	0.01	-71.95	-28.5
5	99 (A)	0.01	-70.86	-28
6	98 (A)	0.01	-70.34	-28
7	99 (A)	0.01	-70.55	-26.5
8	99 (A)	0.01	-71.44	-26.5
9	99 (A)	0.01	-72.07	-26.5
10	99 (A)	0.01	-73.38	-26.5
11	99 (A)	0.01	-74.52	-26.5
12	99 (A)	0.01	-76.58	-28
13	99 (A)	0.01	-78.76	-28

4.4.3. 27th Avenue Wi-Fi Spectrum Survey

Table 33 shows the duty cycle, average and maximum signal levels across all channels in the 2.4 GHz wireless range for the 27th Avenue test site. Data was collected using a Wi-Spy spectrum analyzer and Chanalyzer software in January and February of 2010. Note the software grades the channels for communication link use, with "A" being the best.

The interference survey was completed over several days to show the variability of interference not only for the various channels but also with the time of day and the day of the month. For instance the average interference on channel 6 varied by 20 dB or a factor of 100 from January 22 to February 2. Note that all the dates are Fridays at about 3:30 PM except February 2, 2010, which was a Tuesday. Testing was done on this day at about noon.

Table 33: Wireless Survey for 27th Avenue – part 1.

January 22nd 2010						January 29th 2010				
Channel	Grade	Duty Cycle %	Average (dBm)	Max (dBm)		Channel	Grade	Duty Cycle %	Average (dBm)	Max (dBm)
1	99 (A)	0.01	-78.7	-32.0		1	93 (A)	0.04	-89.7	-43.5
2	99 (A)	0.01	-76.5	-29.0		2	94 (A)	0.04	-89.4	-43.5
3	99 (A)	0.01	-75.4	-29.0		3	96 (A)	0.03	-90.0	-43.5
4	99 (A)	0.02	-74.1	-29.0		4	98 (A)	0.02	-84.5	-33.0
5	99 (A)	0.02	-73.6	-29.0		5	97 (A)	0.02	-82.1	-31.5
6	99 (A)	0.02	-73.1	-29.0		6	97 (A)	0.02	-81.7	-31.5
7	99 (A)	0.01	-72.8	-28.5		7	98 (A)	0.02	-81.6	-31.5
8	99 (A)	0.01	-72.8	-28.5		8	99 (A)	0.02	-83.1	-31.5
9	99 (A)	0.01	-71.9	-25.5		9	99 (A)	0.02	-82.6	-31.5
10	99 (A)	0.01	-72.6	-25.5		10	99 (A)	0.02	-85.7	-33.0
11	99 (A)	0.01	-73.6	-25.5		11	99 (A)	0.02	-86.5	-33.0
12	99 (A)	0.01	-75.0	-25.5		12	99 (A)	0.02	-86.8	-33.0
13	99 (A)	0.01	-78.1	-25.5		13	100 (A)	0.04	-96.8	-52.0

Table 34: Wireless Survey for 27th Avenue – part 2.

February 2nd 2010						February 12th 2010				
Channel	Grade	Duty Cycle %	Average (dBm)	Max (dBm)		Channel	Grade	Duty Cycle %	Average (dBm)	Max (dBm)
1	99 (A)	0.08	-82.8	-45.5		1	100 (A)	0.01	-88.6	-35.5
2	99 (A)	0.08	-82.9	-45.5		2	100 (A)	0.01	-88.6	-35.5
3	99 (A)	0.08	-85.1	-47.0		3	100 (A)	0.01	-89.7	-35.5
4	99 (A)	0.06	-92.1	-51.0		4	100 (A)	0.01	-90.2	-37.5
5	99 (A)	0.04	-96.0	-53.0		5	100 (A)	0.01	-90.0	-37.5
6	99 (A)	0.04	-95.9	-53.0		6	100 (A)	0.01	-89.1	-35.0
7	99 (A)	0.04	-94.9	-53.0		7	100 (A)	0.01	-89.0	-35.0
8	99 (A)	0.05	-88.6	-48.0		8	100 (A)	0.01	-88.9	-34.0
9	99 (A)	0.04	-88.1	-48.0		9	100 (A)	0.01	-86.1	-32.5
10	99 (A)	0.04	-87.2	-48.0		10	100 (A)	0.01	-86.2	-32.5
11	99 (A)	0.04	-86.7	-48.0		11	100 (A)	0.01	-86.9	-32.5
12	100 (A)	0.04	-87.4	-48.0		12	100 (A)	0.01	-87.0	-32.5
13	100 (A)	0.03	-90.6	-49.5		13	100 (A)	0.01	-91.3	-32.5

5. DISCUSSION

While the intent of this project was to implement and evaluate the MeshBox system, a number of challenges were noted in testing that a worth summarizing here so that others who intend to conduct similar research and development are aware of them.

MeshBox communication could be affected greatly by the presence of other WiFi transmitters such as home wireless networks. This is due to the fact that in-band transmitters increase the noise power seen by a receiver, making the desired signal more difficult to detect. The typical solution is to increase the transmitter power or reduce the link distance, which is usually not an option.

Since our testing was done at a height of six feet above the ground, an increase in node elevation would improve the Fresnel zone clearance and, thus, long distance performance. The Fresnel zone is the area that the radio waves travel through after leaving the antenna. Typically 20 percent blockage of the Fresnel zone produces little signal loss, but more than 40 percent blockage causes significant signal loss.[12] The six-foot node height above the ground is the 20 percent blockage point for 528-foot spacing at 2.4 GHz.

For a distance of 1,056 feet, transmitting at a frequency of 2.4 GHz, the Fresnel zone radius is 10.4 feet (Figure 24**Error! Reference source not found.**). The Fresnel zone radius increases as the distance between transmitter and receiver increases. We had 43 percent Fresnel zone blockage at the 1,056-foot distance and 53 percent blockage at the 1,584-foot distance. This accounts for at least part of the poor performance seen during the tests.

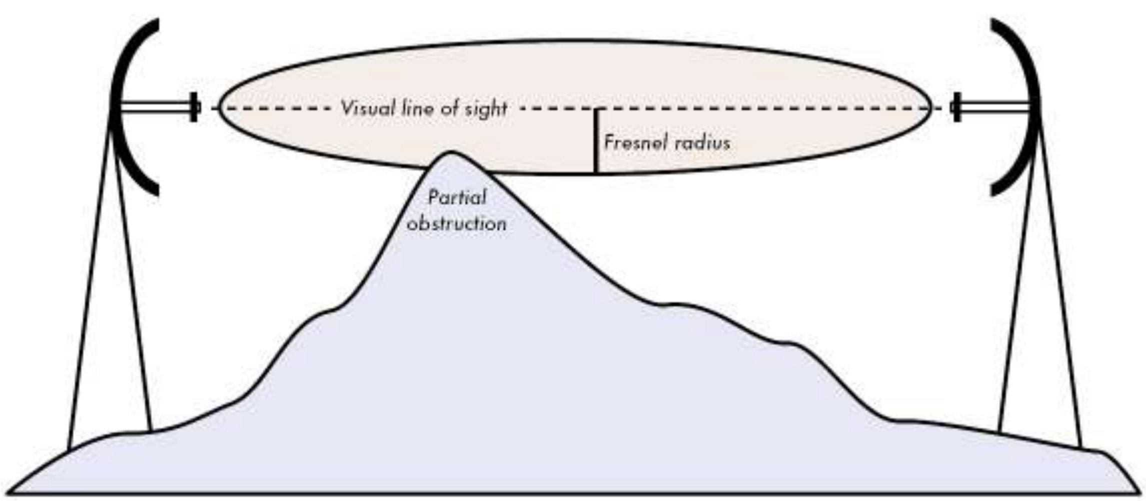


Figure 24: Fresnel Zone Example, Image Courtesy of VIAS.org[13]

For best performance, the MeshBoxes should have a line-of-sight communication path. It is also recommended that the MeshBox antennas are positioned in the same geometric plane and aligned vertically as seen in Figure 3 (not bent). The Type N adaptor the MeshBoxes use is prone to coming loose, which can cause problems if the antenna connection also loosens. Also, if the adaptor is loose, it will twist rather than snug up, which will stress the cable inside the MeshBox going from the Type N adaptor to the PCB.

Moreover when the MeshBoxes were powered by internal batteries, we noticed some MeshBoxes did not operate as long as others, and signal integrity would begin to fade as battery power was drained. To eliminate this problem, starting in October 2009 a large external 12 VDC power pack was used to power the MeshBox for testing. This provided more consistent test results. The internal batteries were disconnected when the external power pack was used.

When evaluating network performance, all units should have been tested with a designated base unit. That base unit should not have been changed unless it was incompatible with the desired test parameters. Antenna performance should have been measured to enable matching of antennas with similar performance for testing, or use the same antennas for all tests. Only one parameter at a time should have been varied when testing so comparisons could be made with confidence. Also test results should have been reviewed for validity soon after performing any tests so that retesting could be done immediately if the data is inconsistent.

6. CONCLUSIONS

The MeshBoxes perform well during controlled testing at distances of 528 feet or less, and the performance at distances from 528 feet to 1,056 feet is acceptable. Communication between MeshBoxes at distances greater than 1,056 feet is not reliable and even in near ideal conditions the performance is below the minimum acceptable SNR of 10 dB. Performance would be improved by mounting the MeshBoxes at 10 feet or more above any obstructions to reduce Fresnel zone blockage.

An internal battery is convenient but can severely limit the operation of the network. Large external battery supplies are a more viable option when setting up a temporary mesh network. Although more expensive, use of industrial rated wireless routers is also highly recommended for reliability reasons.

Few commercial alternatives to the MeshBoxes are available and most are designed for the military. None have an internal power source. Some examples are given below.

Rajant Corp. – BreadCrumb

This is a portable mesh network developed for military, mining, and first responder applications. It operates in the 900 MHz, 2.4 GHz, 4.9 GHz and 5 GHz bands with multiple radios in a single unit. Of particular interest is the new Rajant BreadCrumb JR, which measures 7.319” x 1.480” x 1.383” (see http://www.rajant.com/products/breadcrumb-jr). This device is not only portable, it is wearable.

MeshDynamics Inc. – MD4000

This is a hybrid mobile mesh system developed for government entities and operates in the WiFi and 4.9GHz bands with multiple radios in a single unit.

Telos Corp. – I-STAMS

Integrated Secure Tactical Area Mesh System (I-STAMS) is a hybrid mesh wireless system for classified or unclassified services. It appears mainly intended for government mobile wireless systems.

In general, the MeshBoxes served the purpose for conducting the demonstration associated with the MANETS project, but inconsistent operation precluded further testing for transportation applications. Most of the project was spent trying to characterize problems and performance of the system as it was developed. As mentioned above, it would have been better to purchase and use industrial rather than consumer-grade equipment. However, at that time, there were no known systems of this kind and quality that are based on an open operating system (Linux), allowing for the flexibility in configuration and testing that was desired of this system.

7. RECOMMENDATIONS

The project produced several recommendations. These include improving testing procedures, further researching transportation applications for mesh networks,, and using industrial grade components to produce a reliable system that would yield reproducible results.

7.1. Improved Testing

When testing link performance record data for both link radios.

Record at least five separate readings for each link to enable calculation of reasonable average values.

Take pictures of test setup showing location of antenna on vehicle, orientation of antennas to one another, direction that the vehicle is oriented with respect to antennas, etc.

Find a test location with level ground and little elevation change over a distance of 0.3 – 0.4 miles. This location should also have little interference from other WiFi transmitters. Have all testing done at the same location and in the same manner to facilitate data evaluation.

7.2. Transportation Applications

While a system to communicate along the roadway may be useful it is only as useful as the applications it facilitates. During a demonstration of this system on the DHS MANETS project it was necessary to create an application that made use of a mesh network. Applications for mesh networks in transportation are relatively unexplored. Research could be performed in mesh network applications for transportation.

7.3. Research into Mesh Networks for Transportation

The current scope of the project included building and testing of a mesh network communication system. However, during the project, limitations of the Mesh software used in the system became apparent. For transportation applications a mesh protocol should deal well with node mobility and should be robust when a network is in the form of a linear array such as on a roadway.

7.4. Reproducible System

As the MeshBox is constructed from a consumer grade wireless router, great system improvements could be made by using an industrial grade single-board computer and radios.

The MeshBox hardware was selected primarily for low cost but also for compatibility with a known version of OpenWRT and for the small size of the printed circuit board. The use of the selected wireless router is sufficient for a proof of concept project but was found lacking when considered for further development and production. Many transportation professionals have asked how they could get their own MeshBox and had to be told that the current system was not reproducible.

Moving to a reproducible system could be done with commercial industrial hardware. The software in use, OpenWRT, is simply a version of LINUX that is compatible with many single board computers designed for wireless router use. A variety of radios compatible with such computers and are offered in 802.11a/b/g/n and 900 MHz.

Moving to such a system would require further work. The MeshBox system currently uses preconfigured software in the form of firmware “updates” that are built by third parties. Actual configuration for our system is limited to add-on packages for testing and visualization. Use of an industrial computer would require installation and possible compilation of the LINUX kernel and utilities. Installation or compilation of hardware drivers would possibly be required. However, with research before selection of the equipment, hardware incompatibilities could be minimized and the process could be simplified.

To ensure a reliable long distance link, for example at a range of 0.4 miles (2,112 feet) over level terrain, the MeshBoxes should be mounted at a minimum of 15 feet above the ground. A long-distance link may also be obtained with minimum Fresnel zone blocking and shorter MeshBox mounting height by crossing a low area such as a creek or gulley.

An improved battery system is recommended. The battery system currently employed by the MeshBoxes is not reliable and as such was not used at all during the latest testing. Tethering the MeshBoxes to an external supply is not as convenient as internal power but reduces mounting structure requirements because of the ligher weight, and makes charging the batteries or swapping power supplies simpler. For the greatest reliability, external power would be necessary.

It would also be interesting to investigate the Freifunk software to determine the nature in which it measures received signal strength indication (RSSI), noise and bandwidth. Testing signal to noise ratio (SNR) and bandwidth (BW) could be done concurrently and occasionally the two attributes do not correlate.

8. PRESENTATIONS AND PAPERS

8.1. WSRTTIF, Mt Shasta, CA

The MeshBox system was demonstrated to transportation technology professionals during the 2008 Western States Rural Transportation Technology Implementers Forum (WSRTTIF) in Mount Shasta, CA. Nodes were deployed around the Mount Shasta Resort, with Internet connectivity provided by a WTI trailer using an EV-DO cellular modem. The conference room where the forum was being held was a small distance away, but the resort's walls decreased the wireless signal such that it required a number of nodes in a serial network to reach the conference room. The MeshBox demonstrated the self-forming and self-healing aspects of mesh networks with a series of nodes in a path to the conference room. The network formed a five-hop mesh with Internet connectivity. A number of the transportation professionals' present displayed interest in the system with some requesting MeshBox units for testing.

8.2. Mesh Technology Demonstration, Hot Springs County, WY

The MeshBox system was used in a demonstration of mesh technology for public safety officials from Hot Springs County, WY, 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 2,000 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 occupations. Along with law enforcement and fire personnel, there were many attendees that were responsible for communications including dispatchers, communication supervisors, engineers, and program management for the statewide communication system.

8.3. NRITS Conference, Anchorage AK

The MeshBox system was presented to transportation professionals at the National Rural ITS (NRITS) conference in Anchorage in September 2008. In general, there was great interest in the technology and the associated project. It was emphasized, however, that the system developed was only suitable for demonstrations and testing.

9. APPENDIX

Testing results tables:

Tables 35–37 are Node 7 test results for the WTI test location. RSSI and noise tests were completed at 528 feet, 1,056 feet and 1,584 feet. Refer to section 4.3.3 for setup details.

Table 35: SNR Test Results for Node 7 at 528 feet at WTI.

Parameter / Test No.	Antenna 12			Antenna 17		
	RSSI (dBm)	Noise (dBm)	SNR (dB)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	-72	-92	20	-71	-92	21
2	-71	-95	24	-71	-90	19
3	-76	-90	14	-69	-84	15
4	-71	-92	21	-72	-92	20
5	-71	-93	22	-67	-87	20
6	-72	-95	23	-65	-96	31
7	-74	-88	14	-71	-93	22
8	-71	-95	24	-69	-84	15
9	-71	-93	22	-67	-82	15
10	-71	-92	21	-67	-93	26
Average	-72	-92.5	20.5	-68.9	-89.3	20.4

Table 36: SNR Test Results for Node 7 at 1,056 feet at WTI.

Parameter / Test No.	Antenna 12			Antenna 17		
	RSSI (dBm)	**Noise (dBm)**	**SNR (dB)**	**RSSI (dBm)**	**Noise (dBm)**	**SNR (dB)**
1	-77	-95	18	-79	-96	17
2	-76	-90	14	-77	-90	13
3	-76	-96	20	-79	-92	13
4	-77	-87	10	-76	-95	19
5	-76	-96	20	-76	-93	17
6	-76	-93	17	-77	-90	13
7	-77	-90	13	-77	-93	16
8	-76	-87	11	-77	-96	19
9	-77	-95	18	-79	-95	16
10	-76	-88	12	-79	-96	17
Average	-76.4	-91.7	15.3	-77.6	-93.6	16

Table 37: Test Results for Node 7 at 1,584 Feet at WTI.

Parameter / Test No.	Antenna 12			Antenna 17		
	RSSI (dBm)	**Noise (dBm)**	**SNR (dB)**	**RSSI (dBm)**	**Noise (dBm)**	**SNR (dB)**
1	-87	-84	-3	-82	-92	10
2	-84	-90	6	-85	-93	8
3	-82	-88	6	-88	-92	4
4	-84	-93	9	-84	-92	8
5	-85	-88	3	-84	-90	6
6	-85	-95	10	-84	-92	8
7	-85	-93	8	-84	-84	0
8	-84	-96	12	-80	-85	5
9	-87	-90	3	-82	-95	13
10	-87	-93	6	-84	-90	6
Average	-85	-91	6	-83.7	-90.5	6.8

Tables 38–40 show Node 10 test results for the WTI test location. RSSI and noise tests were completed at 528 feet, 1,056 feet and 1,584 feet. Refer to section 4.3.3.2 for setup details.

Table 38: SNR Test Results for Node10 at 528 feet at WTI.

Parameter / Test No.	Antenna 12			Antenna 17		
	RSSI (dBm)	Noise (dBm)	SNR (dB)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	-62	-84	22	-63	-90	27
2	-63	-92	29	-67	-88	21
3	-62	-84	22	-69	-95	26
4	-65	-93	28	-62	-93	31
5	-65	-92	27	-62	-90	28
6	-62	-90	28	-63	-93	30
7	-65	-95	30	-67	-96	29
8	-62	-93	31	-65	-92	27
9	-62	-95	33	-65	-92	27
10	-60	-93	33	-63	-90	27
Average	-62.8	-91.1	28.3	-64.6	-91.9	27.3

Table 39: SNR Test Results for Node 10 at 1,056 feet at WTI .

Parameter / Test No.	Antenna 12			Antenna 17		
	RSSI (dBm)	**Noise (dBm)**	**SNR (dB)**	**RSSI (dBm)**	**Noise (dBm)**	**SNR (dB)**
1	-67	-96	29	-71	-95	24
2	-69	-95	26	-72	-93	21
3	-67	-98	31	-71	-85	14
4	-69	-90	21	-74	-85	11
5	-69	-88	19	-72	-93	21
6	-71	-87	16	-72	-95	23
7	-69	-85	16	-72	-92	20
8	-67	-96	29	-76	-88	12
9	-71	-85	14	-71	-93	22
10	-67	-90	23	-72	-92	20
Average	-68.6	-91	22.4	-72.3	-91.1	18.8

Note the anomalous grayed-out data in Table 40 is not included in the average.

Table 40: SNR Test Results for Node 10 at 1,584 feet at WTI.

Parameter / Test No.	Antenna 12			Antenna 17		
	RSSI (dBm)	Noise (dBm)	SNR (dB)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	-49	-98	49	-82	-90	8
2	-43	-90	47	-87	-93	6
3	-49	-90	41	-85	-92	7
4	-40	-88	48	-49	-88	39
5	-46	-93	47	-45	-92	47
6	-43	-95	52	-48	-93	45
7	-43	-93	50	-46	-92	46
8	-45	-90	45	-46	-93	47
9	-46	-85	39	-46	-92	46
10	-43	-93	50	-40	-93	53
Average	-44.7	-91.5	46.8	-45.7	-91.9	46.2

Tables 41–43 are Nodes 6, 9 and 11 test results, respectively, for the Durston test location. BW tests were completed at 528 feet for the three nodes.

Table 41: BW Test Results for Node 6 at Durston.

Parameter / Test No.	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	-59	-79	20
2	-62	-92	30
3	-60	-90	30
4	-62	-87	25
5	-65	-93	28
6	-62	-93	31
7	-61	-98	37
8	-62	-91	29
9	-66	-83	17
10	-59	-83	24
Average	-61.8	-88.9	27.1

Table 42: BW Test Results for Node 9 at Durston.

Parameter / Test No.	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	-60	-87	27
2	-65	-79	14
3	-67	-95	28
4	-62	-93	31
5	-63	-90	27
6	-62	-84	22
7	-60	-90	30
8	-67	-77	10
9	-60	-87	27
10	-65	-80	15
Average	-63.1	-86.2	23.1

Table 43: BW Test Results for Node 11 at Durston.

Parameter / Test No.	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	-62	-90	28
2	-60	-90	30
3	-62	-93	31
4	-60	-82	22
5	-67	-88	21
6	-62	-93	31
7	-63	-77	14
8	-60	-88	28
9	-60	-93	33
10	-63	-80	17
Average	-61.9	-87.4	25.5

Table 44 and

Table 45 show test results at 528 feet and 1,056 feet, respectively, for Nodes 10 (base) and 7 (relay) at the 27th Avenue test site. Ten tests were performed at each distance.

Table 44: SNR and BW Test Results from 27th Avenue at 528 Feet. Base Node: 10, Relay Node: 7.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	4.40	6.10	-66	-83	17
2	6.01	7.26	-67	-93	26
3	5.41	7.87	-71	-93	22
4	6.81	7.99	-71	-84	13
5	5.37	1.93	-67	-91	24
6	5.70	7.07	-72	-86	14
7	6.17	6.65	-72	-83	11
8	3.71	4.73	-72	-85	13
9	5.84	7.65	-70	-83	13
10	6.00	7.77	-70	-83	13
Average	5.5	6.5	- 69.8	- 86.4	16.6

Table 45: SNR and BW Testing at 27th Avenue at 1,056 Feet. Base Node: 10, Relay Node: 7.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	0.04	2.7	-80	-82	2
2	0.0	0.77	-77	-85	8
3	0.01	2.13	-79	-82	3
4	0.07	1.86	-80	-80	0
5	0.12	1.32	-78	-93	15
6	0.07	1.08	-78	-81	3
7	0.01	0.88	-77	-93	16
8	0.04	1.33	-78	-95	17
9	0.92	2.26	-80	-95	15
10	0.54	2.28	-80	-85	5
Average	0.2	1.7	- 78.7	- 87.1	8.4

Table 46 through 53 show test results at 528 feet for Nodes 2, 3, 6, 7, 8, 9, 10 and 11, respectively, with Node 5 acting as base station.

Table 46: SNR and BW Testing at 27th Avenue at 528 Feet. Base Node: 5, Relay Node: 2.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	2.49	2.15	-64	-94	30
2	3.86	2.24	-66	-84	18
3	2.96	1.82	-63	-83	20
4	3.21	2.16	-64	-83	19
5	3.01	2.11	-66	-76	10
Average	3.1	2.1	- 64.6	- 84.0	19.4

Table 47: SNR and BW Testing at 27th Avenue at 528 Feet. Base Node: 5, Relay Node: 3.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	2.54	1.86	-65	-85	20
2	2.56	2.16	-64	-79	15
3	2.32	1.26	-64	-82	18
4	2.05	1.40	-64	-73	9
5	2.38	1.85	-65	-79	14
Average	2.4	1.7	- 64.4	- 79.6	15.2

Table 48: SNR and BW Testing at 27th Avenue at 528 Feet. Base Node: 5, Relay Node: 6.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	1.74	1.83	-64	-79	15
2	1.47	1.28	-65	-86	21
3	1.90	1.98	-65	-81	16
4	2.29	2.08	-65	-82	17
5	2.56	2.08	-65	-95	30
Average	2.0	1.9	- 64.8	- 84.6	19.8

Table 49: SNR and BW Testing at 27th Avenue at 528 Feet. Base Node: 5, Relay Node: 7.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	3.39	2.67	-72	-88	16
2	3.87	2.38	-74	-87	13
3	3.01	2.14	-75	-89	14
4	3.92	2.83	-73	-93	20
5	4.02	2.58	-73	-90	17
Average	3.6	2.5	- 73.4	- 89.4	16.0

Table 50: SNR and BW Testing at 27th Avenue at 528 Feet. Base Node: 5, Relay Node: 8.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	3.58	3.27	-74	-94	20
2	3.24	3.13	-72	-92	20
3	2.76	1.61	-74	-91	17
4	3.05	2.20	-74	-88	14
5	3.76	3.31	-72	-94	22
Average	3.3	2.7	- 73.2	- 91.8	18.6

Table 51: SNR and BW Testing at 27th Avenue at 528 Feet. Base Node: 5, Relay Node: 9.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	2.63	1.01	-71	-77	6
2	2.70	1.53	-72	-97	25
3	2.97	1.57	-71	-79	8
4	1.51	1.26	-72	-82	10
5	2.32	1.80	-69	-96	27
Average	2.4	1.4	- 71.0	- 86.2	15.2

Table 52: SNR and BW Testing at 27th Avenue at 528 Feet. Base Node: 5, Relay Node: 10.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	3.81	1.97	-65	-88	23
2	3.68	2.79	-64	-79	15
3	5.16	2.58	-65	-84	19
4	2.78	2.25	-62	-86	24
5	2.52	1.37	-64	-94	30
Average	3.6	2.2	- 64.0	- 86.2	22.2

Table 53: SNR and BW Testing at 27th Avenue at 528 Feet. Base Node: 5, Relay Node: 11.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	3.77	2.15	-65	-72	7
2	3.55	1.78	-66	-83	17
3	3.63	2.22	-65	-82	17
4	2.62	1.20	-64	-93	29
5	3.47	1.41	-67	-94	27
Average	3.4	1.8	- 65.4	- 84.8	19.4

Table 54 shows test results at 1,056 feet for Node 11 with Node 10 acting as base station.

Table 54: SNR and BW Testing at 27th Avenue at 1,056 Feet. Base Node: 10, Relay Node: 11.

Parameter / Test No.	BW Up (Mbps)	BW Down (Mbps)	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	2.30	2.07	-75	-97	22
2	1.20	0.09	-76	-79	3
3	3.15	1.37	-72	-95	23
4	4.23	2.83	-75	-80	5
5	4.06	0.67	-73	-84	11
6	3.46	0.38	-76	-76	0
7	3.87	2.42	-73	-87	14
8	1.43	1.84	-75	-97	22
9	1.35	0.20	-76	-92	16
10	1.48	1.92	-77	-86	9
Average	2.65	1.38	-74.8	-87.3	12.5

Table 55 shows SNR test results at 1,056 feet for Node 10 with a router acting as base station.

Table 55: SNR Test Results at 27th Avenue at 1,056 Feet. Node Under Test: 10.

Parameter / Test No.	RSSI (dBm)	Noise (dBm)	SNR (dB)
1	-69	-84	15
2	-74	-87	13
3	-76	-84	8
4	-71	-88	17
5	-71	-77	6
6	-72	-85	13
7	-69	-79	10
8	-76	-92	16
9	-74	-85	11
10	-76	-85	9
Average	- 72.8	- 84.6	11.8

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