QuRiNet: A Wide-Area Wireless Mesh Testbed for Research and Experimental Evaluations

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***Abstract*—Research in wireless mesh networks have been growing in recent years. Many testbeds have been created to study networking protocols in wireless mesh networks. In this work, we describe QuRiNet, an outdoor wide-area wireless mesh network deployed in a natural reserve. We describe various research efforts that have been leveraging the QuRiNet testbed. Several interesting measurement data are reported in addition to their impact due to various network configurations and technological variations. Mesh nodes in QuRiNet are powered by solar panels, running with multiple radios. QuRiNet provides the backbone for transporting ecological and environmental data from the field to the labs. The goal of deploying QuRiNet is to create a research platform for advance wireless mesh networking research. Physical link distances in QuRiNet range from hundreds to thousands of meters. QuRiNet has been used for experimental research studies including: channel assignment, network monitoring, and mobility studies.**

I. Introduction

Wireless mesh networks (WMN) have become widely studied the past few years [1]. Early studies used numerical analysis and computer simulations to study large scale wireless networks. To validate the algorithms and techniques that came out of research, experimental testbeds were built. These started as small five to ten node networks situated indoors, but moved on to twenty-plus node networks deployed in outdoor environments in the last few years.

The Quail Ridge Wireless Mesh Network (QuRiNet) is a wide-area wireless mesh testbed deployed in an outdoor environment, far from any other interfering network or wireless signals. Is is deployed at the Quail Ridge Natural Reserve located near Lake Berryessa in Napa Valley. The Reserve is owned, operated, and maintained by the University of California system. QuRiNet is continually use to provide detailed measurements and security studies to help design better network protocols. The testbed is frequently used for validating results and newly-designed protocols. In addition, QuRiNet is the primary communication infrastructure for the Reserve and thereby supports dozens of ecological and environmental research being undertaken at the Reserve.

The size, capabilities, and accessibility of QuRiNet is continually being expanded. Currently, it has 34 operational nodes. The aerial view of QuRiNet is shown in Figure 1. All nodes, except the gateway nodes, use solar power due to the lack of connectivity to the power grid. Each node's location is based on the researchers' and connectivity needs. One node has been deployed on a floating buoy to help wirelessly transport data from underwater sensors.

Unlike other mesh networks, QuRiNet is deployed in an outdoor, interference-free environment. Distances between nodes range from hundreds to thousands of meters. Roofnet, one of the earliest mesh networks, is deployed as a community rooftop wireless mesh network [2]. This network has to compete with home wireless networks for the wireless channel. ORBITLab took a different approach to studying wireless networks by building an indoor wireless network in a grid pattern [3]. They setup a network to study the wireless characteristics in a controlled environment. QuRiNet is unique, in that, it is setup to study wireless mesh networks in an actively used environment.

Our contributions in this paper include:

1) a detailed description of QuRiNet
2) a list of research challenges for wireless mesh networks
3) measurement data of an outdoor wireless mesh network

The paper is outlined as follows: We start with a background on wireless mesh networks in Section II. Section IV motivates the need for this mesh network. Then in Section III, we describe the environment QuRiNet is deployed in. Section V details the QuRiNet mesh network infrastructure. Section VI provides measurement data from QuRiNet within the last few years. Section VII lists research studies that have been done or currently underway in QuRiNet. Finally, we conclude this paper with the future plans in Section VIII.

II. Background

Wireless mesh networks research grew out of wireless local area network (WLAN) research. WLAN research concentrated on single hop local coverage, with a wired distribution system for routing the data between wireless clients and their destination. At most, two wireless hops are used, one near the wireless source, and the other at the destination. The problem with this approach is the core of the network is still based on wired technology.

Wireless mesh networks were introduced to remove the wired technology from the core. All routing of data is done through the wireless medium as the distribution system. This allowed for rapid deployment and tear down of networks for different applications. It also allowed for deployment in areas where running wires is infeasible or cost ineffective.

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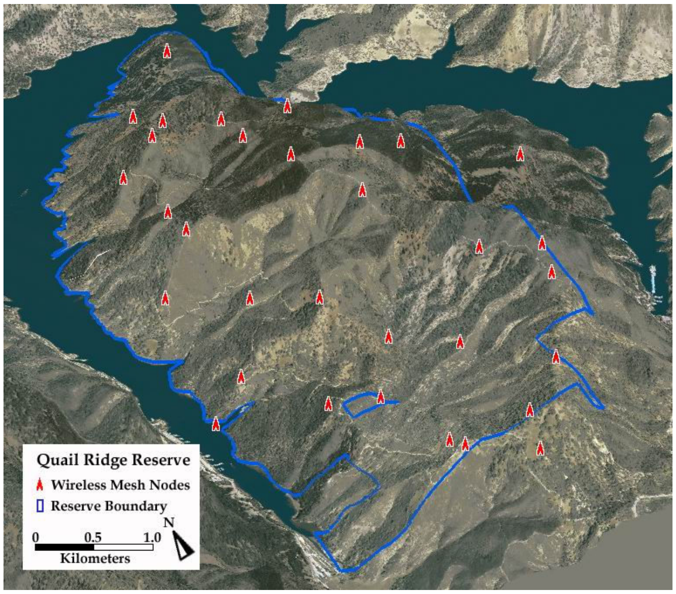


Figure 1. QuRiNet Aerial View

Early wireless mesh network research began either as a small experimental testbed (less than five nodes) or as a simulation setup. Simulation allowed for large-scale testing without the cost. It also allowed for research across all layers without dealing with hardware problems. However, simulation of wireless networks were never perfect. Channel conditions can not be simulated accurately [4].

As time went on, researchers expanded their experimental testbeds to larger and larger systems. With more and more wireless off-the-shelf products available, testbeds became cheaper to build. Early testbeds were small indoor setups [5]–[7].

MIT Roofnet, one of the earliest, outdoor wireless mesh networks, was built as a community mesh network [2], [8]. In exchange for wireless connectivity, users deployed the wireless nodes in their apartments and the antennas placed on the roofs. This network focused on the link connectivity between wireless nodes. No extra wireless coverage was provided for mobile nodes. Distances between nodes are in the range of hundreds of meters.

In a completely different direction, ORBITlab was built as an indoor network platform [3]. It is not a production system, but rather a research platform for testing network protocols. Hundreds of wireless nodes are setup in an indoor grid. A support system allowed researchers to run their own software on the platform to carry out their research needs. While ORBITlab provides high flexibility in running wireless tests, there are still some drawbacks. Because this system is setup in an indoor environment, many of the results will not translate directly for outdoor mesh networks. The distances between two mesh nodes are short compared to outdoor mesh networks. The traffic load is also determined by the researchers, and usually not based on realistic workloads.

The UCSB meshnet is another indoor wireless mesh network [9]. It focused on building two parallel wireless mesh networks, with one for live testing, and the other to carry monitoring data. This allowed the researchers to study the mesh network without hindering the traffic flow.

All of these early mesh networks were setup to study specific aspects. QuRiNet is setup for more general wireless network research in a different kind of environment.

III. Quail Ridge Natural Reserve

QuRiNet is situated in the Quail Ridge Natural Reserve in California. The reserve is maintained by the UCD Natural Reserve System and consists of approximately 2,000 acres of wilderness and hilly terrain. The main objective of the reserve is to allow researchers to conduct experiments and study the flora and fauna in the area.

The reserve has many hills and valleys with a densely forested canopy in some areas. A small number of ponds can be found in the reserve depending on the weather in a particular year. Poison oak grow in patches around the area, along with many California native plants. Man-made dirt roads and trails crisscross the reserve to allow for hiking and vehicles.

Deers, wild turkeys, frogs and snakes make their homes here in the reserve. An occasional mountain lion wanders into and out of the reserve every now and then. Researchers have also studied mice in the area. Bats dwell in some of the darker areas around the reserve.

The climate in the Quail Ridge Reserve is seasonal. Heavy rainfall can be expected in the winter months. During the summer, the temperature goes up and dries the ponds. The temperature also differs between the hilltops and valleys during the day. Valleys get less sunlight and prone to colder weather in the mornings.

IV. Motivation and Challenges for QuRiNet

There are many motivations for building a wireless mesh network in Quail Ridge:

1) **Ecological researchers would like to gather data during times when physical access to the reserve is difficult.** Winter months are usually the worst for data gathering when the rain makes driving through the reserve impractical. A wireless mesh network will also allow constant updates to researchers in their offices without stepping into the field.
2) **Quail Ridge offers minimal wireless interference for wireless testing.** Unlike urban areas where WiFi signals are everywhere and on every frequency band, Quail Ridge has a clean wireless spectrum. There are few neighboring homes and businesses that have wireless access points to contend with anything we build in Quail Ridge.
3) **The outdoor environment provides different challenges than indoor buildings.** Distances between outdoor nodes can go up to a mile, so signal quality varies a lot in the network. Transmission power and antenna

receiving sensitivity is important when trying to obtain the best signals.

4) **The variation of terrain in the area offers different conditions for study.** Quail Ridge contains line of sight on some hilltops to each other, while a dense canopy cover the valleys. The terrain ranges from wide open spaces to isolated forested locations.
5) **QuRiNet is a testbed designed for collaboration with other researchers.** Many researchers do not have the access to a wireless mesh network for testing new networking protocols. QuRiNet can be leveraged to help in this area. As a research platform, QuRiNet is made to study different networking protocols.
6) **QuRiNet allows for wireless communication studies with multiple overlapping collision domains.** By building the mesh network outdoors, multiple collision domains are created due to the layout and distance. This allows researchers to study hidden node and exposed node problems in experimentation.

In building QuRiNet, some technical challenges need to be overcome:

1) **Remote location:** Quail Ridge is located an hour from Davis and makes quick hardware reboots impossible. Mesh nodes inside the reserve are scattered in different areas of accessibility. Remote upgrades need to be made more reliable.
2) **Terrain variations:** Line of sight becomes a problem in wireless connectivity in the valleys. Hilltop nodes need directional antennas to point directly to valley nodes for more long distance communications. Nodes in the valley can communicate with each other, but special setups are needed for valley-to-hilltop communication.
3) **Seasonal weather:** The mesh nodes are subjected to a varying range of temperature. The weatherproof boxes where the nodes are located get extremely hot in the summer. Rain becomes a problem to the wireless signals during the winter. Day and night also brings changes in temperature at different parts of the reserve. In the valleys, nodes will suffer more cooler weather, while hilltop nodes will need to withstand higher temperatures.
4) **Live network:** Software changes on the nodes must be planned to minimize the impact of live traffic. Even through QuRiNet is a mesh network, nodes must be updated in an organized fashion without interrupting the connectivity between the gateways to all anodes.
5) **No out-of-band communication:** Unlike most indoor testbeds, QuRiNet contains no direct wired network between sites. Couple with the limited memory on the mesh nodes, it becomes a challenge to log all data without affecting the normal traffic. Special protocols must be implemented for management and monitoring of the network.
6) **Node time synchronization:** Time synchronization is already hard over wireless channels due to differences in delay. It is even harder in a wireless multihop setting where nodes can be as far as five or six hops away.
7) **Power issues:** All the sites in QuRiNet (except the Field Station) are powered by solar energy. All computations and power draws must be minimized to conserve as much energy as possible during the winter months when a week can go by without sunlight in some areas.
8) **Remote Experimentations:** Since QuRiNet is situated away from our labs, remote testing becomes a major concern. QuRiNet experiments needs to be designed in such a way that tests are automated and repeatable. Allowing other researchers to use the network remotely also introduces security problems.

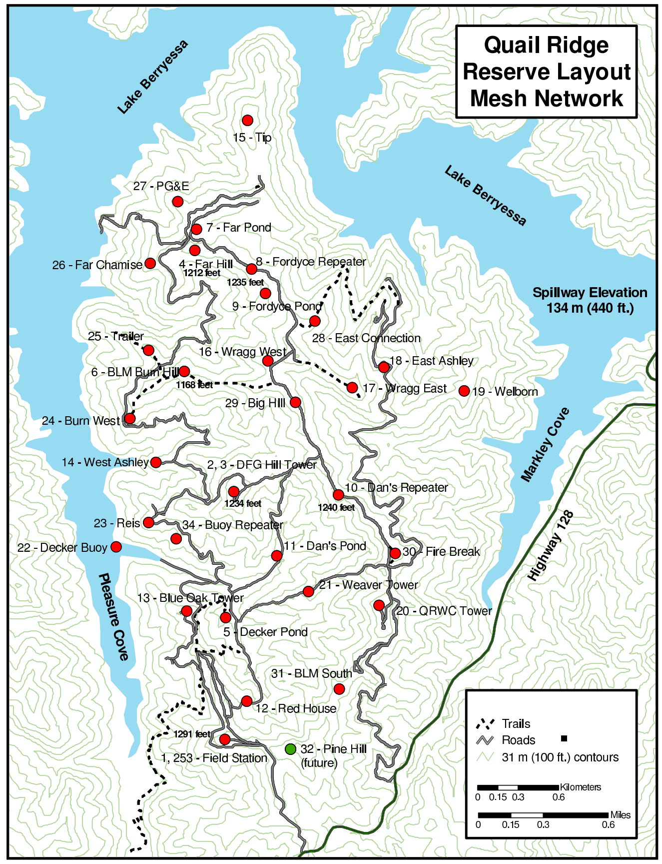


Figure 2. QuRiNet Site Locations as of May 13, 2009

V. QuRiNet Infrastructure

There are currently 34 mesh nodes in QuRiNet which are located at 31 physical sites. The location of the sites are shown in Figure 2. QuRiNet is located in a hilly and densely forested region so wireless signals behave differently than an indoor or single plane setup.

A. *Mesh Nodes*

The deployed nodes in the mesh network are all built using Soekris net4826 embedded boards (Figure 3). Each node has a 266MHz 586 processor, 128MB SDRAM and flash storage ranging from 64MB to 256MB. For the wireless radios, we equipped each board with two Atheros 802.11b/g Mini-PCI cards. Radios running on 802.11b/g standard can use three

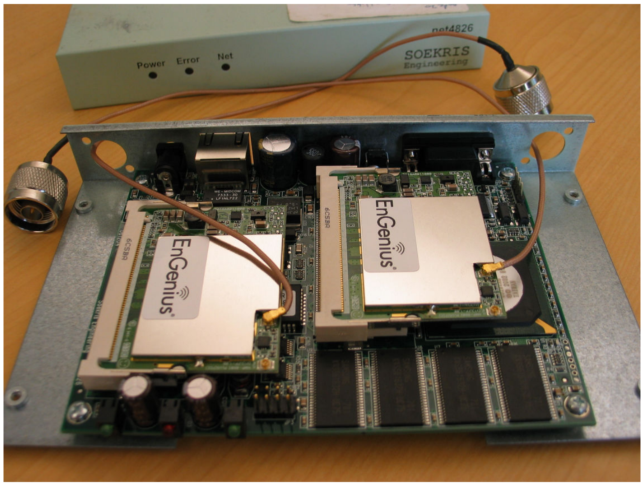


Figure 3. QuRiNet mesh node

non-overlapping channels. We tried running the IEEE 802.11a protocol but found the 5.2GHz to have poor propagation for the distances and transmission power in QuRiNet.

All nodes run a custom Linux distribution using kernel 2.6.28 with a modified wireless device driver. The routing protocol used is OLSR [10]. Directional antennas are located on certain nodes to provide higher signal strength as planned backhaul links. All other nodes use omni-directional antennas.

B. Mesh Sites

There are 31 physical sites in QuRiNet that house the mesh nodes. Some sites have multiple mesh nodes to provide higher wireless capacity. There are three sites with two nodes each: Field Station, DFG Hill Tower and the Tip. All sites, except the Field Station use solar energy to power their nodes.

The Field Station site is the **gateway** to the Internet. In addition to having two mesh nodes, it contains a living space for researchers and a server room for all mesh network equipment. A T1 line connects the UC Davis campus to the mesh network. A high performance server is used for firewall, gateway, and monitoring service. Since this site is the main bottleneck to the mesh network, we installed two omni-directional and two directional antennas to increase wireless capacity usage. The directional antennas point to DFG Hill and Dan's Repeater sites.

The next highest point in the reserve is the DFG Hill site (Figure 4). This site also contains two nodes on a 30-foot tower. It has two directional antennas and one omni-directional antenna. Because of its location, it can connect to many of the sites in the valleys and around the reserve. One directional points to the Field Station, while the other goes deeper into the reserve and points to the Far Hill site.

One of the very first sites deployed was Decker Pond (Figure 5). Ecological researchers use this location for frog research. It contains a omnidirectional for local coverage and a directional antenna back to the DFG Hill Tower site. This site is also equipped with many video cameras and weather gauges for environmental monitoring. The disadvantage of this

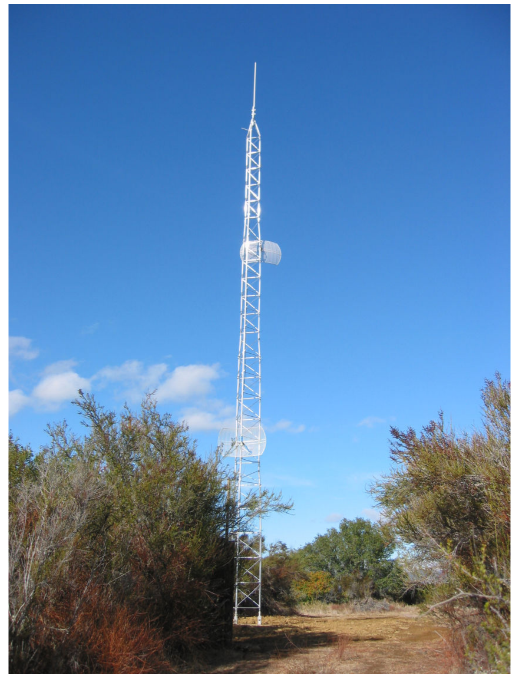


Figure 4. DFG Hill Tower Site

Figure 5. Decker Pond Site

site is it's location in a valley where sunlight is limited by the foliage. More batteries and more solar panels are used to keep all the equipment up and running.

More recently, we've deployed a site on water. Decker Buoy (Figure 6) is specially made and floats on water equipped with water sensors. This site is anchored just off of the reserve flanked by two hills. Because of its random rotations on water, we used omni-directional antennas at this site to communicate back to a repeater site on one of the hills (Decker Buoy Repeater site).

Only the some select sites have directional antennas to give it an additional boost in signal quality to a neighboring site (Table I). Other sites in the mesh network use omni-directional antennas for communications. All other sites are made from pipes and cement filled tires as the base. This allows some mobility when relocation is needed. Guide wires are used to stabilize the sites.

Site Number	Site Name	Antennas	Features
1	Field Station	2 directional, 1 omni	T1 line, server, gateway, 30ft tower
2	DFG Hill	2 directional, 1 omni	video camera, wind and soil sensors, 40ft tower
3	Buoy Repeater	2 omni	10ft pole
4	Far Hill	1 directional, 2 omni	10ft pole
5	Decker Pond	1 directional, 1 omni	video camera, rain sensor
6	BLM Burn	2 omni	10ft pole
7	Far Pond	2 omni	video camera, 10ft pole
8	Fordyce Repeater	2 omni	10ft pole
9	Fordyce Pond	2 omni	10ft pole
10	Dan's Repeater	1 directional, 1 omni	10ft pole
11	Dan's Pond	1 directional, 1 omni	acoustic sensor
12	Red House	2 omni	10ft pole
13	Blue Oak	1 directional, omni	40ft tower
14	West Ashley	2 omni	10ft pole
15	Tip	3 omni	10ft pole
16	Wragg West	2 omni	10ft pole
17	Wragg East	2 omni	20ft tower
18	East Ashley	2 omni	10ft pole
19	Welborn	2 omni	10ft pole
20	QRWC Tower	2 omni	30ft tower
21	Weaver Tower	2 omni	30ft tower
22	Decker Buoy	2 omni	on water
23	Reis	2 omni	10ft pole
24	Burn West	2 omni	10ft pole
25	Trailer	2 omni	10ft pole
26	Far Chamise	2 omni	10ft pole
27	PG&E	2 omni	10ft pole
28	East Connection	2 omni	10ft pole
29	Big Hill	2 omni	10ft pole
30	Fire Break	2 omni	10ft pole
31	BLM South	2 omni	10ft pole

Table I
QURINET MESH SITES

Figure 6. Decker Buoy Site

C. QuRiNet Components

- **Solar Power**: All nodes in QuRiNet run on solar power, except for the ones attached to the Field Station site. The solar panels and battery quantities differ at each site, depending on the amount of equipment and the amount of sunlight throughout the year. Sites in the valleys like Decker Pond have much more batteries and solar panels for faster charging, longer sustainability during cloudier days.
- **Software Protocols**: QuRiNet has a few unique software systems running to help in our experimentations. These include monitoring, measurements, and management. On the monitoring side, we have special agents in the nodes that report periodically the link and network level information back to the central server at the gateway. Measurements can be done through the daemons running at each node. Management of the mesh nodes can be done remotely through ssh or scripts, to control the nodes. These include link layer parameters like channel number, modulation rates, and transmission power. At the network layer, we can control the routing protocols and firewalls.

VI. MEASUREMENT DATA

This section details measurements made at QuRiNet. We include temporal and spatial information.

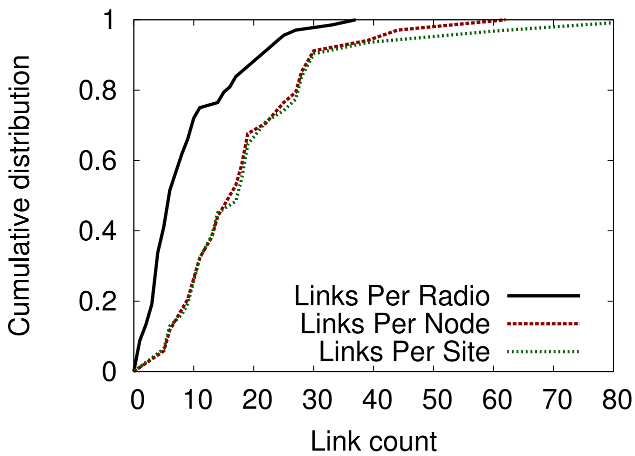


Figure 7. QuRiNet Link Count CDF

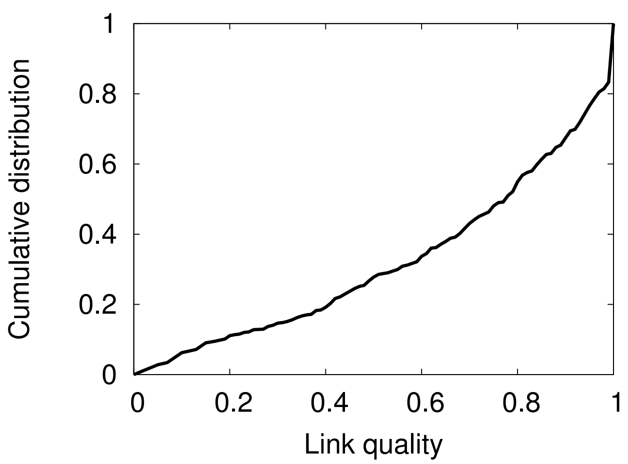


Figure 8. QuRiNet Link Quality CDF

A. Link Counts

Figure 7 contains the link distribution among the radios, nodes and sites. There is an average of 8 links per radio, with a minimum of 1 and a maximum of 34. The radio with 34 links is located at DFG Hill Tower (in the middle of Figure 2). This site is one of the highest peaks in Quail Ridge so it has a good line of sight to most other sites.

The distribution of links between nodes and sites are similar since only three sites have multiple nodes. One single site has a maximum of 78 links, which means it can hear 78 links in the network if all this site's radios are on the same channel. Clearly, if we do not separate the radios on to different channels, there will be a lot of interference.

B. Link Qualities

Figure 8 shows the cumulative distribution of the link qualities in QuRiNet. The total number of potential links in QuRiNet is 556. There are 464 directional wireless links, 68 links are through the PCI bus, and 24 are through Ethernet. There are 194 bidirectional wireless links, and another 76 that are single direction only (i.e. one radio can hear another, but not vice versa). The minimum link quality for all links is 0.05, while the maximum is 1.00. The average link quality is 0.728. About 25% of the links have the highest link quality and 20% of the links have lower than 0.5 probability of success.

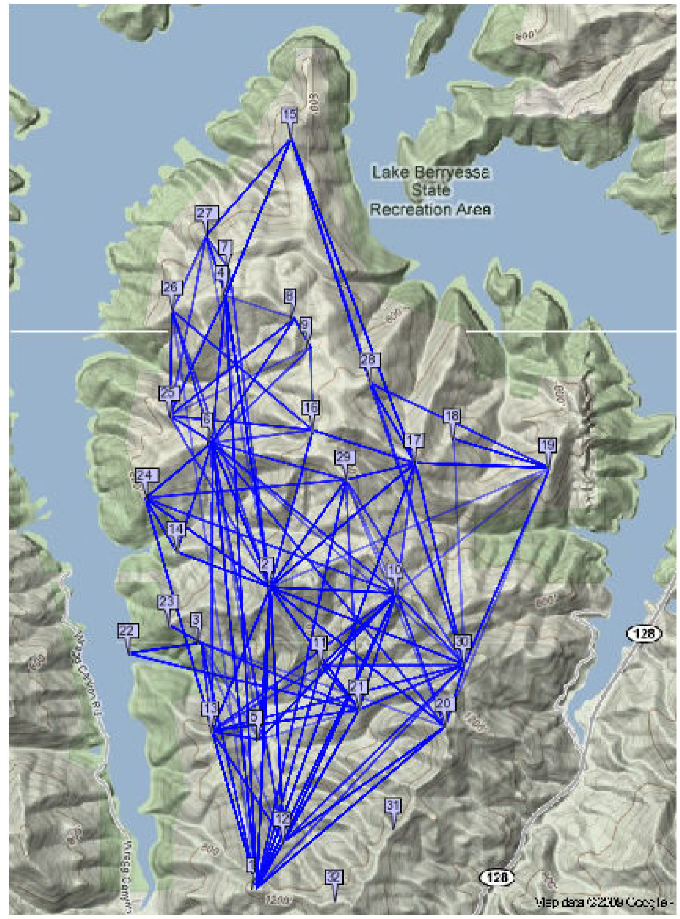


Figure 9. Network Links Connectivity

C. Spatial Location of Links

Figure 9 provides a spatial mapping of all the neighbor information between all sites. Site 2 connects to many of the surround sites in a wheeled configuration. Site 1, with it's directional antenna can receive signals from many of the farther sites too. The outliers of site 15, site 22, site 18, and site 19 have very few neighbors. The terrain is hindering site 18's connectivity to one of its closes neighbor (site 17). Site 23 also has the same problem due to the slope of the mountain it is next to.

D. Distance to Gateway

From the gateway's perspective, we can see how many radios in the network are a certain number of hops away (Figure 10) from a link perspective. This information does not take into account of routing, which may force data to take longer paths. Zero hops mean they are located at the gateway site. The QuRiNet topology is very shallow, but branches out

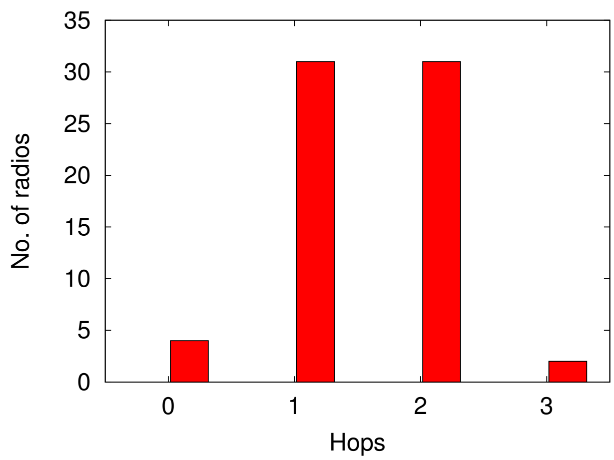
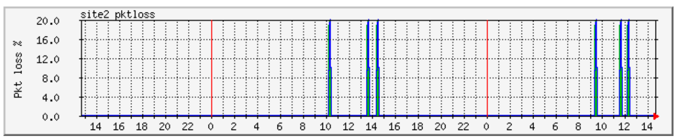
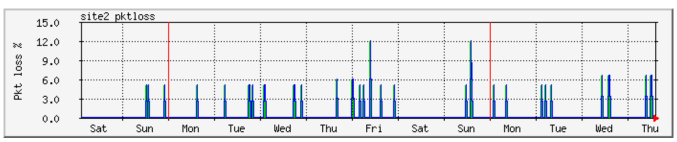


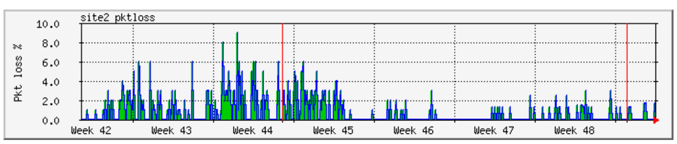
Figure 10. Radio Hop Distance to Gateway



(a) Day



(b) Week



(c) Month

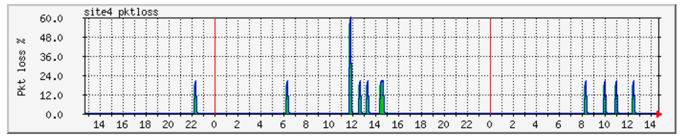
Figure 11. DFG Hill - Site 2 Node to Gateway Performance

widely. This type of topology is good if all the data travels from the gateway to the radios. The short number of hops will decrease the latency in the system, which will improve the quality of multimedia applications in the network.

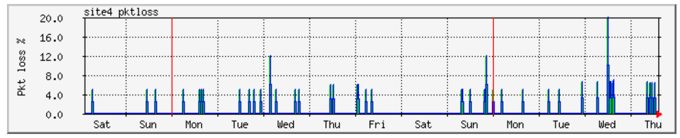
E. Gateway to Node Performance

QuRiNet has an obligation to periodically transmit sensor data from some sites to the central server at the gateway site. This means performance from the gateway to the node is very important. In this section we take a look at the performance of certain sites to the gateway over time to see their behaviors. Performance is measured by probing ten probing packets every ten minutes. In this section, we look at the most recent day, week, and month of each site to see how they performed.

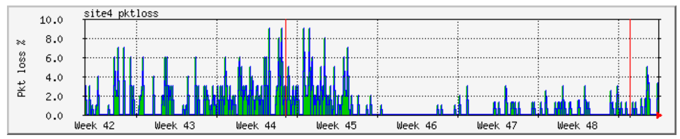
The DFG Hill site (Site 2) has a very good path performance from the gateway (Figure 11). This is due to the direct single hop connection using directional antennas at both ends. The most packet loss percentage is 20%, but it only occurs in very



(a) Day

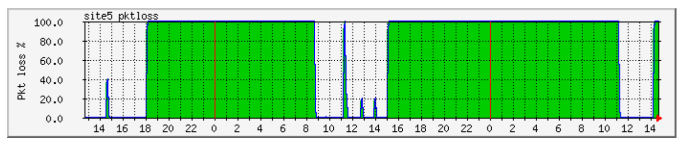


(b) Week

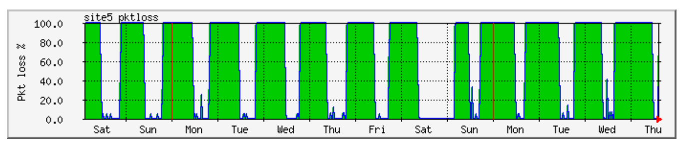


(c) Month

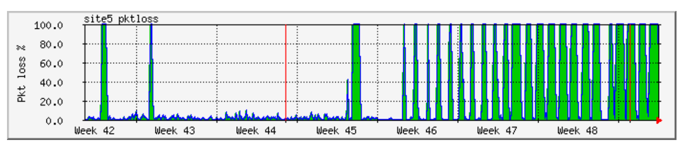
Figure 12. Far Hill - Site 4 Node to Gateway Performance



(a) Day



(b) Week



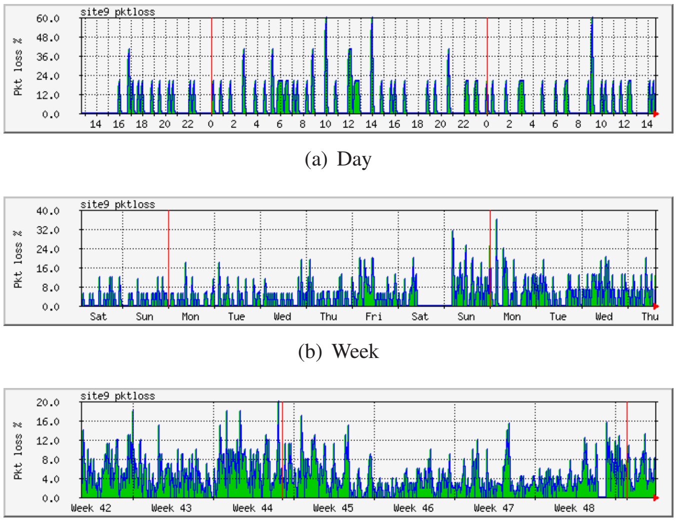
(c) Month

Figure 13. Decker Pond - Site 5 Node to Gateway Performance

short periods of time. From the monthly graph (Figure 11(c)), there were more losses during the weeks from 42 - 45. The only explanation for the increased losses is the wind speed. During that month, there were no extra rain, but there were higher wind levels. Since the directional antennas are situated on 30ft towers, it would explain more losses when the antennas oscillate with the tower.

Figure 12 shows the performance of the Far Hill site. Like the DFG Hill site, Far Hill suffers from the increased wind during week 42 -45 (Figure 12(c)). Because this site also uses a directional antenna to communicate with site 2 (and then to the gateway), it is susceptible to wind.

Down in the valley, is the Decker Pond site (Figure 13). Unlike other sites, this one is equipped with a lot of sensor and video equipment. It also gets the least sunlight due its

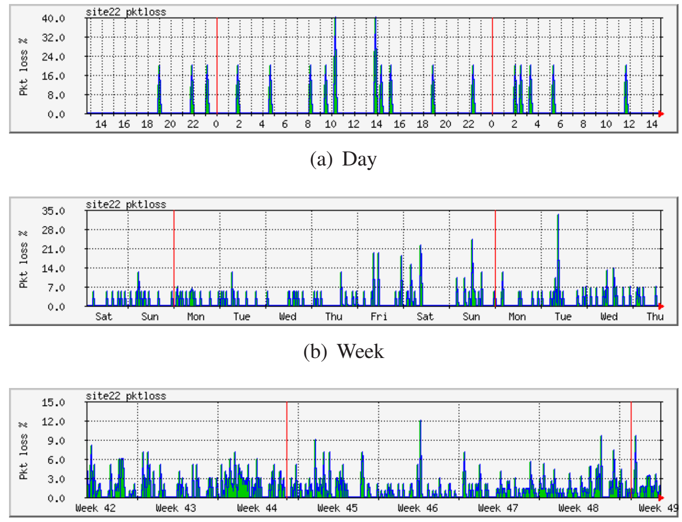


(a) Day

(b) Week

(c) Month

Figure 14. Fordyce Pond - Site 9 Node to Gateway Performance

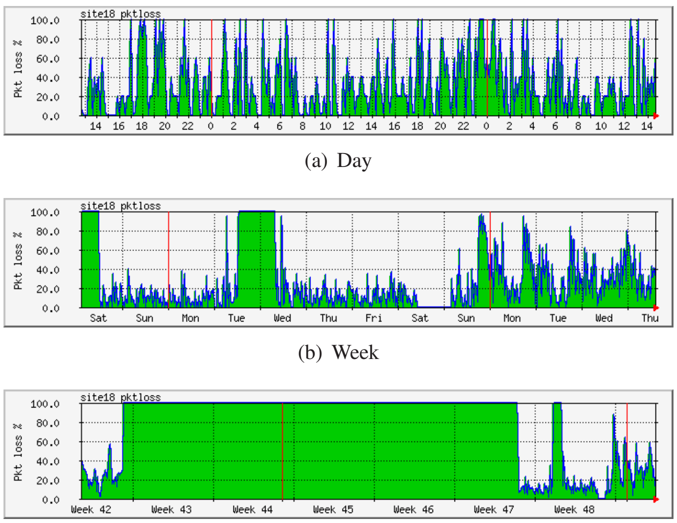


(a) Day

(b) Week

(c) Month

Figure 16. Decker Buoy - Site 22 Node to Gateway Performance



(a) Day

(b) Week

(c) Month

Figure 15. East Ashley - Site 18 Node to Gateway Performance

location. As seen in Figure 13(a), this site is disconnected from the network from long periods of time. In this case, it is only operational between 9 and 3pm everyday, for the last three weeks (Figure 13(b)). With winter upon us, the solar panels get less time to charge the batteries and the site powers down when there's no power. From Figure 13(c), the weeks between 43 and 45, Decker Pond was up continuously.

Fordyce Pond, another pond site, behaves pretty consistently (Figure 14). It does have packet losses every so often due to its distance from the gateway (4 wireless hops). However, even though this pond is situated in a valley, it still has a clear view of the Sun during the day.

Unlike other sites, East Ashley (site 18) gave us the most trouble. It is situated in a farther location than other sites but it has ample sunlight. As seen in Figure 15, it's connectivity is poor. If we were to deploy more sites, we would need to add more neighbors to this site for better connectivity.

Considering Decker Buoy is on water and is situated in a valley, it has very good performance (Figure 16). This site is anchored in place, but will rotate with the wind. Because of this characteristic, we had to use omnidirectional antennas. The site usually takes 2-3 hops to get to the gateway, so there are less losses in transit.

VII. Research Applications

QuRiNet is a testbed for improving the state of the art in wireless mesh networks. In this sense, all researchers are welcome to suggest new protocols or experiments to run on the network. This section gives an overview of the research projects that have been completed or currently underway in QuRiNet.

A. Channel Assignment

QuRiNet is a multi-radio, multi-channel wireless mesh network, which means a mesh node can be on multiple channel frequencies at the same time due to the multiple wireless interfaces it contains. Having multiple interfaces allows the network to be partitioned so interfering links are on different channels. This will decrease the number of collisions and contention in the channel, and increase the throughput capacity per node.

We compared different static channel assignment algorithms in QuRiNet [11]. The algorithms include breadth-first search, priority-based selection, and integer linear programming based solutions. To drive the algorithms, we first measured the link qualities in the network, as well as the neighborhood information. For each algorithm's channel-to-radio mapping result, we tested their performance in the network against a series of tests. These include end-to-end performance, neighbor counts, and susceptibility to interfering nodes.

B. Rate and Route Adaptations

In a collaborative work, we have looked at rate and route adaptation problems in wireless mesh networks through QuRiNet. This study looked at mapping the link qualities (packet delivery ratios) and the RSSI information for each link to give better information to the rate control and routing protocols. Current mesh networks are not sharing enough information for rate control and routing protocols to make smart decisions. This project studied what information and how to use this information for rate control and routing.

C. Queuing Theory Evaluations

In another collaborative work, we evaluated queuing models through experiments. By setting up the same network layout as the model, we feed the system with the same traffic generation rates to see how closely the theoretical model behaved compared to the experiments.

D. Mobility Experiments

QuRiNet lends itself very nicely to mobility experiments. The terrain in the reserve offers a wide variety of situations for mobile mesh nodes. Mobile nodes can be carried by a walking person or attached to an all-terrain-vehicle. With the reserve's size, large mobile experiments can be conducted without interference. Currently, a study is being conducted on hybrid mesh networks with mobile nodes leveraging the backbone of QuRiNet. We are looking at the wireless link characteristics to see how that information can be applied to higher layer protocols.

E. Bandwidth Estimation

We've also leveraged QuRiNet to study bandwidth estimations in wireless networks [12]. Wireless channels have varied available bandwidth depending on time and the source-destination pairs. We've looked at comparing different bandwidth estimation tools and their accuracy in wireless networks. As a more reliable method of bandwidth estimation, we've introduced a passive method for bandwidth estimation.

F. Network Management, Measurements, and Monitoring

Remote network management and monitoring is a major concern in wireless networks. Being able to perceive link quality and traffic information from a single location will help network administrators (and centralized algorithms) make better decisions. Current management protocols like SNMP are not designed specifically for wireless networks. With too much periodic information, the links closest to the central server can be bogged down. New protocols are needed for better periodic and event driven mesh network information.

On a related issue with the management protocol, the management interface is also very important. A system administrator needs a way to view and configure all the network parameters with a touch of a button. In network research, it is important to log and trace packet information so analysis can be done offline. QuRiNet has a special logging functionality that minimizes traffic overhead [13], [14].

VIII. Future Plans

We have presented QuRiNet, an outdoor wireless mesh network. We've gone into detail about the terrain of the reserve and the challenges of QuRiNet. The current mesh network is based on IEEE 802.11b/g technology.

With the evolution of wireless technologies, we will continuously update QuRiNet with the latest technologies for state-of-the-art research. Current plans include adding 802.11n setups and WiMAX mesh nodes for heterogeneous research and capacity improvements. By adding in MIMO-based technologies, researchers can study the outdoor usefulness of the MIMO techniques.

Other enhancements include deploying Software Defined Radios (SDR) into the field for research studies. Current SDR studies focus on indoor testbeds. We plan to bring the research to an outdoor environment for long distance and real-world testing. By adding SDR into QuRiNet, we can study channel-width allocation techniques and other research made possible only by accessing the physical layer parameters.

QuRiNet upgrades are not planned just for the underlying physical layer, but also for higher layers. The future plans include developing a better routing algorithm that is multi-channel and multi-radio aware. Current routing protocols, like OLSR, lack sufficient information to choose the best routes for this type of network. Future routing protocols will need to have crosslayer feedback and control mechanisms with link and physical layers, as well as higher layers.

The management plane for QuRiNet will also be updated. This will include enhanced measurement and monitoring capabilities in QuRiNet. Unlike many of the current mesh networks that have an out-of-band interface for all debugging needs, QuRiNet does not have this luxury. In order to do real-time monitoring and measurements, new algorithms and techniques must be developed to minimize the impact on user traffic.

Plans have also been developed to inter-connect other Natural Reserves with QuRiNet to study very long distance links. Instead of having remote sites communicate through the Internet, we can study data sharing needs between remote reserves. By introducing new technologies and techniques, we plan to open up more avenues of research in QuRiNet.

One of the main future goals for QuRiNet is remote access for collaborative research. We plan to share the data collected at QuRiNet with other researchers to study and compare with their testbeds. Currently, we split our objective into four phases:

- Read-only access through web interface. Researchers will be allowed to download and make inferences to the data collected at QuRiNet.
- User-level access to mesh nodes for traffic load testing. We plan to allow researchers to generate specific traffic loads to test the network robustness.
- Limited access for network and protocol configurations. As part of our ongoing efforts, we will manually adjust the network configurations for researcher testing.
- Full access to mesh node configurations. Ultimately, we

plan to automate all the tests and configurations so remote researchers can apply and run their tests.

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