Dear Author,

Please check your proof carefully and mark all corrections at the appropriate place in the proof (e.g., by using on-screen annotation in the PDF file) or compile them in a separate list. To ensure fast publication of your paper please return your corrections within 48 hours.

For correction or revision of any artwork, please consult http://www.elsevier.com/artworkinstructions.

No queries have arisen during the processing of your article.

Thank you for your assistance.
QuRiNet: A wide-area wireless mesh testbed for research and experimental evaluations

Daniel Wu, Dhruv Gupta, Prasant Mohapatra

Department of Computer Science, University of California, Davis, CA 95616, United States

Abstract

Research in wireless mesh networks has 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. QuRiNet comprises of over 30 wireless nodes, spread over 2000 acres of wilderness. QuRiNet provides the backbone infrastructure for transporting ecological and environmental data from the natural reserve to the on-campus laboratories. Mesh nodes in QuRiNet are powered by solar energy, and comprise of multiple radios per node. Physical link distances in QuRiNet range from hundreds to thousands of meters. A parallel goal of deploying QuRiNet is to create a novel platform for advanced research in wireless mesh networks. In this report, we share our experiences in the deployment and maintenance of QuRiNet in its unique setting. We also describe various research efforts that have been leveraging the QuRiNet testbed. Several interesting measurement results are reported, along with the impact of various network configurations and technological variations on the functionality of the testbed. QuRiNet has been used for a variety of experimental studies including: channel assignment, network monitoring, and mobility studies. Current and future study plans include experimental evaluations of various security and reliability research.

1. Introduction

Wireless mesh networks (WMNs) have been 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 5–10 node networks situated in indoor environments, but moved on to 20+ node networks deployed in outdoor settings 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. It 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 Natural Reserve System. QuRiNet is continually used 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 communications infrastructure for the reserve and thereby supports dozens of ecological and environmental research projects being undertaken there.

The size, capabilities, and accessibility of QuRiNet is continually expanding. Currently, it has 35 operational nodes. An aerial view of QuRiNet is shown in Fig. 1. All nodes, except the gateway node, use solar power due to lack of connectivity to the power grid. Each node’s location is based on both the researchers’ needs and connectivity constraints. One node has been deployed on a floating buoy to help transport data from underwater sensors over the wireless medium.
Unlike most 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]. However, 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. We provide a detailed description of the deployment experience in QuRiNet, along with details of various hardware and software used in the testbed. We also describe the environment in which the testbed is deployed, and how it supports various types of ecological and environmental research projects.

2. We describe several research challenges for wireless mesh networks that are currently being evaluated at QuRiNet. Various network protocols and algorithms have been evaluated at this testbed. Moreover, we provide a comprehensive overview of various future studies that plan to use this testbed.

3. Lastly, we provide extensive measurement results from an outdoor wireless mesh network. Our results provide great insights into the intricacies and functioning of a live wireless testbed.

The paper is outlined as follows: In Section 2, we describe the environment QuRiNet is deployed in. Section 3 motivates the need for this mesh network. Section 4 provides the challenges of deploying this network. Section 5 details the QuRiNet mesh network hardware and software systems. Section 6 provides measurement data from QuRiNet within the last few years. Section 7 lists research studies that have been done or currently underway in QuRiNet. Section 8 contains information on the online data graphs for QuRiNet. Finally, we conclude this paper with the future plans in Section 9.

2. Quail Ridge Natural Reserve

QuRiNet is situated in the Quail Ridge Natural Reserve in California. The reserve is maintained by the University of California Natural Reserve System and consists of approximately 2000 acres of wilderness and hilly terrain. The main objective of the reserve is to allow researchers to conduct experiments and analyze ecological impacts related to flora, fauna, and animals.

The reserve has many hills and valleys with a densely forested canopy in some areas. Elevation can go as high as 1300 ft at the highest peaks. The reserve contains three to four ponds depending on the weather in a particular year. Poison oaks grow in patches around the area, along with many native California plants. Man-made dirt roads and trails criss-cross the reserve to allow for hiking and all-terrain 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 and bats in the area.

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 are prone to cooler weather in the mornings.

3. Background and motivation

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 was that the core of the network was still based on wired technology.

Wireless mesh networks (WMN) were introduced to remove the wired system 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 was infeasible or costly.

Early WMN 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 of deploying an actual network. It also allowed for research across all layers without dealing with hardware problems. However, simulations of wireless networks were never perfect. The interference and propagation models used in simulator tools were based on simplifying assumptions and approximations. Moreover, channel conditions cannot be simulated accurately in a simulator [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 real-life 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 of mesh networking. QuRiNet is setup for more general wireless network research in a different kind of environment, focusing primarily on non-interfering spectrum. Such an environment is suitable for fine-grained sensitivity studies that could help design and analyze the impact of new protocols.

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 Wi-Fi 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. The clean spectrum environment provides a complementary testbed environment to several existing urban-area testbeds. Researchers can analyze various cause-and-effects while designing new protocols.

3. The outdoor environment provides different wireless characteristics 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 covers 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 and analyze design alternatives.

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.

4. Deployment challenges

This section will detail the challenges of deploying a wireless mesh network in a natural reserve. The main objective of the deployment is wireless coverage, especially for areas that are studied by ecological researchers. QuRiNet started in the summer of 2005. Fig. 2 shows a timeline of the site deployments. We split this section into three parts: choosing suitable locations for our mesh nodes, the challenges of weather, and equipment considerations during the deployment.

4.1. Choosing suitable sites

Choosing sites for the mesh network deployment is challenging. There are three requirements we needed to keep in mind: human access, sunlight availability, and line of sight. In order for setup and maintenance of sites, we need to be able to get to each site. The reserve has a main dirt road loop that can be used for travel.

Certain areas of the reserve are covered by forested canopy with limited access to sunlight. In order to use solar power at these sites, suitable locations need to be found to avoid filling the site with dozens of batteries.

Locating sites with good human access and sunlight are great, but network connectivity between sites are important too. When spotting a site, we need to make sure the location can allow connectivity between it and at least two other sites (for reliability purposes).

There are 33 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 earliest three sites deployed are the Field Station, DFG Hill, and Decker Pond. We chose the Field Station due to the already existing infrastructure and the...
connection to the power grid. This site already had a T1 line to UC Davis campus, and sits at one of the highest point in the reserve. It serves as the gateway to the rest of the mesh network.

The Field Station site serves as 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 (Fig. 3) and Dan’s Repeater sites.

From the Field Station, we selected DFG Hill as the next hop for the mesh network. DFG Hill is also one of the highest points in the reserve, and allowed a line of sight connection between DFG Hill and the Field Station. Human access to this point is tricky. We have to drive down into a valley and then wrap around DFG Hill to get to the highest point. Because of the brush in the area, we had to also install a 40 ft tower.

The next highest point in the reserve is the DFG Hill site (Fig. 3). This site also contains two nodes on a 30 ft tower. It has two directional antennas for backhaul connectivity and one omni-directional antenna for local wireless access. One directional points to the Field Station, while the other goes deeper into the reserve and points to the Far Hill site. Because of its location, it can connect to many of the sites in the valleys and around the reserve.

Decker Pond was chosen by an ecological researcher (Fig. 4). He studied the frogs in this pond and would like to get video and audio feeds of the site back to his office. This presented us with a short-term goal when deploying the network. Unlike most sites in the network, this one is within a valley, so network connectivity and sunlight become a problem. This site can actually hear the signal from DFG Hill, but an omni-directional does not allow it to transmit data upwards. In order to solve this problem, we used a directional antenna for direct connectivity to
DFG Hill, and an omni-directional for local access. Decker Pond is unique in the fact that the solar setup (panels and batteries) are not directly attached to the hardware enclosure setup. Due to the trees in the area, one part of the slope is great for the directional antenna to point at DFG Hill, while another has the most sunlight throughout the days. This site is also equipped with many video cameras and weather gauges for environmental monitoring. More batteries and more solar panels are used to keep all the equipment up and running.

More recently, we have deployed a site on water. Decker Buoy (Fig. 5) is specially made and mounted with water sensors. This site is anchored in a channel between two hills just off of the reserve. 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). We find that hardware can be flaky at times. The antenna cables between the antenna and the mesh node can become loose and will not transmit the signal properly.

As mentioned, the Decker Buoy Repeater was deployed as a relay for the buoy. Due to the slope of the hills, there are not many locations that can transmit and receive to the buoy.

4.2. Seasonal weather challenges

Unlike indoor environments, where only the occasional blackout will disrupt a mesh network, an outdoor environment like QuRiNet has to be weatherproof in order to avoid equipment damage. Each site has weatherproof enclosures for the mesh node, the batteries and any other electronic equipment. Even though the boards are protected from the weather, throughout the fall, winter, and spring seasons, rain can become a problem for human access to the sites. The dirt roads can become muddy and vehicles can lose their grip while going up and down the hills.

As far as the mesh nodes are concerned, the seasonal weather changes do not significantly degrade the network performance. Nodes may get really hot during the summer seasons, but they do not affect system operations.

4.3. Equipment considerations

After finding suitable locations for deployment, and protecting the equipment from the weather, we still have to deal with equipment failures and abnormalities. The solar power equipment, towers, enclosures, site bases, and antennas all need to be regularly maintained to provide good reliability for the network.

4.3.1. 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 capabilities 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 a larger number of batteries and solar panels for faster charging, longer sustainability during cloudier days. 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.

When the Red House site was deployed, we had problems with the mesh node rebooting every few seconds. The culprit was a broken charge controller for the solar panels. The voltage it provided was too high.

4.3.2. Towers and enclosures

Each node in QuRiNet is placed in a waterproof enclosure to protect them from the weather. Some enclosures in the network also house the batteries and other networking equipment. Enclosures are attached to either 20 or 40 ft towers (on hill tops) or to a 10 ft pole (in the valleys). The antennas are attached to the towers and poles to clear some of the brush or forest canopy. The sites with 10 ft poles can be moved easily for experiments that are of interest to the ecological researchers.

4.3.3. Site bases

Certain 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.

4.3.4. Antennas

Nodes in QuRiNet use different antennas for different purposes. Backhaul nodes are attached to directional antennas for higher gain, which in turn, will have less frame corruption. The directional antennas are 24 dBi Dicast antennas. Other nodes in the network are attached...
to omni-directional antennas. These have a 7.4 dBi gain and are for the nodes to create ad hoc mesh connections.

Only some selected sites have directional antennas to give them an additional boost in signal quality to a neighboring site (Table 1). Other sites in the mesh network use omni-directional antennas for communications.

4.3.5. Gateway reliability

The purpose of the mesh network is to allow for wireless coverage and also remote access. QuRiNet connects to the Internet through a T1 line. Increasing the number of gateways in the mesh network allows for redundancy. However, with cost and location, installing more T1 lines is infeasible.

In all the years that QuRiNet has been active, the T1 line has intermittent connectivity. Power at the Field Station is located at 33 physical sites. The location of the sites are shown in Fig. 6. QuRiNet is located in a hilly and densely forested region so wireless signals behave differently than an indoor or flat elevation setup.

<table>
<thead>
<tr>
<th>Site number</th>
<th>Site name</th>
<th>Antennas</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Field Station</td>
<td>2 dir, 1 omni</td>
<td>T1 line, server, gateway, 30 ft tower</td>
</tr>
<tr>
<td>2</td>
<td>DFG Hill</td>
<td>2 dir, 1 omni</td>
<td>Video camera, wind and soil sensors, 40 ft tower</td>
</tr>
<tr>
<td>3</td>
<td>Buoy Repeater</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>4</td>
<td>Far Hill</td>
<td>1 dir, 2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>5</td>
<td>Decker Pond</td>
<td>1 dir, 1 omni</td>
<td>Video camera, rain sensor</td>
</tr>
<tr>
<td>6</td>
<td>BLM Burn Hill</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>7</td>
<td>Far Pond</td>
<td>2 omni</td>
<td>Video camera, 10 ft pole</td>
</tr>
<tr>
<td>8</td>
<td>Fordyce Repeater</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>9</td>
<td>Fordyce Pond</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>10</td>
<td>Dan's Repeater</td>
<td>1 dir, 1 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>11</td>
<td>Dan's Pond</td>
<td>1 dir, 1 omni</td>
<td>Acoustic sensor</td>
</tr>
<tr>
<td>12</td>
<td>Red House</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>13</td>
<td>Blue Oak</td>
<td>1 dir, 40 ft tower</td>
<td>40 ft tower</td>
</tr>
<tr>
<td>14</td>
<td>West Ashley</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>15</td>
<td>Tip</td>
<td>3 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>16</td>
<td>Wragg West</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>17</td>
<td>Wragg East</td>
<td>2 omni</td>
<td>20 ft tower</td>
</tr>
<tr>
<td>18</td>
<td>East Ashley</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>19</td>
<td>Wellborn</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>20</td>
<td>OCE Tower</td>
<td>2 omni</td>
<td>30 ft tower</td>
</tr>
<tr>
<td>21</td>
<td>Weaver Tower</td>
<td>2 omni</td>
<td>30 ft tower</td>
</tr>
<tr>
<td>22</td>
<td>Decker Buoy</td>
<td>2 omni</td>
<td>On water</td>
</tr>
<tr>
<td>23</td>
<td>Reis</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>24</td>
<td>Burn West</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>25</td>
<td>Trailer</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>26</td>
<td>Far Chamise</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>27</td>
<td>PG&amp;E</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>28</td>
<td>East</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>29</td>
<td>Big Hill</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>30</td>
<td>Fire Break</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>31</td>
<td>BLM South</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>32</td>
<td>Pine Ridge</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
<tr>
<td>33</td>
<td>QR House</td>
<td>2 omni</td>
<td>10 ft pole</td>
</tr>
</tbody>
</table>

5. QuRiNet hardware and software

There are currently 35 mesh nodes in QuRiNet which are located at 33 physical sites. The mesh network have gone through a number of revisions in the system setup over the years. Due to the increasing number of mesh nodes and devices in the network, the routing and IP addressing scheme had to be changed over time.

From the start of QuRiNet to June 2006, this mesh network used a static routing method for interconnecting the mesh nodes. With the small number of nodes, it was simply a matter of finding the nearest node and using that as the next hop. This presented a number of deficiencies. Some nodes that lose connectivity may bring down the whole network due to its importance in relaying data.

Another problem with the initial setup was the use of public IP addresses. Each node in the network had its own IP address for routing and identification purposes. This allowed administrators to remotely setup and maintain the system from anywhere. However, it also allowed malicious users to attack the individual mesh nodes.

In order to avoid and prevent these problems, the architecture was changed. Instead of static routing, we used a dynamic routing protocol, OLSR [10] with link quality metrics enabled. A dynamic routing protocol allowed a plug-and-play deployment and backup routes in case of failure. Mesh nodes only needed to be hooked up to the solar panels and they can communicate with the rest of the network. When any node goes down (due to power, software or hardware failure), the rest of the network can reroute automatically.

Instead of public IP addresses, we deployed a server as the gateway between the T1 line and the rest of the network. This server has better firewall rules and NAT setup. We can filter out unnecessary data from the Internet to the mesh network, and vice versa. With the NAT setup,
we gain greater flexibility in the IP addressing scheme. We can now do subnet routing instead of just individual IP based routing. It also decouples the public IP addresses to the physical devices. This technique works very well when IP video cameras were deployed. These cameras are attached to a mesh node using an internal IP. A public IP is mapped to this internal private IP so it can be viewed by the rest of the world.

In 2008, we wanted to increase the channel utilization in the network by switching some of the radios to 5 GHz (802.11a). This will allow more non-overlapping channels than on 2.4 GHz. However, the plans failed due to the distances and environmental obstacles. After deploying the 5 GHz antennas, testing showed very low RSSI between mesh nodes. By 2009, all mesh nodes were switched back to using only 2.4 GHz and 802.11b/g.

5.3. Node software development

In 2005, only a handful of Linux distributions supported small storage devices like the Soekris net4826. We chose to use LinuxFromScratch [16] as the development base for our custom Linux distribution. It allowed us to fine tune all the necessary pieces of the system without bloat. This worked very well until we wanted to upgrade individual pieces of the system in a fast, efficient, and portable manner. There was no easy way to keep track of the changes or easily swap out original software for custom ones.

By 2009, we switched the full development to OpenEmbedded [17] and bitbake. This build environment allow a lot of flexibility and reliability. All the source code for the individual pieces are pulled in from their original sources and only when needed. The build environment allowed
changes to be kept track of using the git repository history. It also allowed multiple developers to build from different host machines without worrying about overwriting each other’s changes.

5.4. Remote access

Mesh nodes inside the reserve are scattered in different areas of accessibility. This makes remote access to a mesh node a critical function. Nodes in QuRiNet have ssh serving capability, which allows administrators to access them over the wireless mesh network. This capability is used for both admin-level access, as well as user-level access.

We define users of the QuRiNet mesh network as the network researchers that have been given access to deploy applications or make changes in the network mesh system. By having a secured communication protocol, we can transfer data, files, and do remote testing.

5.5. Software updates

When new applications or software updates are to be deployed into the mesh network, we have three choices. We can install the updates on to extra mesh nodes in the lab, and physically take them out to be deployed by anyone. The second option is to go out to each site individually, and re-image the mesh node. The third option is to remotely install the updates to each mesh node.

5.6. Customization for experiments

QuRiNet has a few unique software systems running to help in our experimentations. These include tools for 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.

Unlike most indoor testbeds, QuRiNet contains no direct wired network between sites. Coupled 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.

Since QuRiNet is situated away from our labs, remote testing becomes a major concern. QuRiNet experiments need 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.

Time synchronization is already hard over wireless channels due to differences in delay. It is even harder in a wireless multi-hop setting where nodes can be as far as five or six hops away.

5.7. Security issues

Even though the mesh network is in a remote area, we still need to protect the network from neighbors and trespassers who may try to piggyback onto the mesh network.

6. Measurement data

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

6.1. Link counts

Fig. 8 contains the link distribution among the radios, nodes and sites. For each radio, we collected the neighboring radios it can overhear, and mark that as a potential link in the network. There is an average of eight 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 Fig. 6). 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.

Fig. 8. QuRiNet link count CDF.
6.2. Link qualities

Fig. 9 shows the cumulative distribution of the link qualities in QuRiNet. The link qualities are determined by the Packet Delivery Ratio (i.e., number of packets successfully received over the total number of packets transmitted). 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.

6.3. Spatial location of links

Fig. 10 provides a spatial mapping of all the neighbor information between all sites. Topology and terrain play a very important role in determining the connectivity at QuRinet. Even though some nodes may be spatially close to each other, they are unable to receive each other’s signals due to variations in topology. Site 2 connects to many of the surround sites in a wheeled configuration. Site 1, with its 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.

6.4. Distance to gateway

From the gateway’s perspective, we can see how many radios in the network are a certain number of hops away (Fig. 11) from a link perspective. This information does not take into account the 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 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.

6.5. 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 10 probing packets every 10 min. 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 (Fig. 12). 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 short periods of time. From the monthly graph (Fig. 12c), there were more losses during the weeks from 42 to 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 30 ft towers, it would explain more losses when the antennas oscillate with the tower.

Fig. 13 shows the performance of the Far Hill site. Like the DFG Hill site, Far Hill suffers from the increased wind during week 42–45 (Fig. 13c). 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 (Fig. 14). Unlike other sites, this one is equipped with a lot of sensor and video equipment. It also gets the least sunlight due to its location. As seen in Fig. 14a, this site is disconnected from the network from long periods of time. In this case, it is only operational between 9 and 3 pm everyday, for the last three weeks (Fig. 14b). With winter upon us, the solar panels get less time to charge the batteries and the site powers down when there is no power. From Fig. 14c, the weeks between 43 and 45, Decker Pond was up continuously.

Fordyce Pond, another pond site, behaves pretty consistently (Fig. 15). It does have packet losses every so often due to its distance from the gateway (four 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 Fig. 16, its 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 (Fig. 17). This site is anchored in place, but will rotate with the wind. Because of this characteristic, we had to use omnidirectional antennas. The DFG Hill site (Site 2) has a very good path performance from the gateway (Fig. 12). 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 short periods of time. From the monthly graph (Fig. 12c), there were more losses during the weeks from 42 to 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 30 ft towers, it would explain more losses when the antennas oscillate with the tower.

Fig. 13 shows the performance of the Far Hill site. Like the DFG Hill site, Far Hill suffers from the increased wind during week 42–45 (Fig. 13c). 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 (Fig. 14). Unlike other sites, this one is equipped with a lot of sensor and video equipment. It also gets the least sunlight due to its location. As seen in Fig. 14a, this site is disconnected from the network from long periods of time. In this case, it is only operational between 9 and 3 pm everyday, for the last three weeks (Fig. 14b). With winter upon us, the solar panels get less time to charge the batteries and the site powers down when there is no power. From Fig. 14c, the weeks between 43 and 45, Decker Pond was up continuously.

Fordyce Pond, another pond site, behaves pretty consistently (Fig. 15). It does have packet losses every so often due to its distance from the gateway (four 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 Fig. 16, its 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 (Fig. 17). This site is anchored in place, but will rotate with the wind. Because of this characteristic, we had to use omnidirectional antennas. The DFG Hill site (Site 2) has a very good path performance from the gateway (Fig. 12). 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 short periods of time. From the monthly graph (Fig. 12c), there were more losses during the weeks from 42 to 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 30 ft towers, it would explain more losses when the antennas oscillate with the tower.

Fig. 13 shows the performance of the Far Hill site. Like the DFG Hill site, Far Hill suffers from the increased wind during week 42–45 (Fig. 13c). 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 (Fig. 14). Unlike other sites, this one is equipped with a lot of sensor and video equipment. It also gets the least sunlight due to its location. As seen in Fig. 14a, this site is disconnected from the network from long periods of time. In this case, it is only operational between 9 and 3 pm everyday, for the last three weeks (Fig. 14b). With winter upon us, the solar panels get less time to charge the batteries and the site powers down when there is no power. From Fig. 14c, the weeks between 43 and 45, Decker Pond was up continuously.

Fordyce Pond, another pond site, behaves pretty consistently (Fig. 15). It does have packet losses every so often due to its distance from the gateway (four 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 Fig. 16, its 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 (Fig. 17). This site is anchored in place, but will rotate with the wind. Because of this characteristic, we had to use omnidirectional antennas. The DFG Hill site (Site 2) has a very good path performance from the gateway (Fig. 12). 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 short periods of time. From the monthly graph (Fig. 12c), there were more losses during the weeks from 42 to 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 30 ft towers, it would explain more losses when the antennas oscillate with the tower.

Fig. 13 shows the performance of the Far Hill site. Like the DFG Hill site, Far Hill suffers from the increased wind during week 42–45 (Fig. 13c). 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 (Fig. 14). Unlike other sites, this one is equipped with a lot of sensor and video equipment. It also gets the least sunlight due to its location. As seen in Fig. 14a, this site is disconnected from the network from long periods of time. In this case, it is only operational between 9 and 3 pm everyday, for the last three weeks (Fig. 14b). With winter upon us, the solar panels get less time to charge the batteries and the site powers down when there is no power. From Fig. 14c, the weeks between 43 and 45, Decker Pond was up continuously.
antennas. The site usually takes 2–3 hops to get to the gateway, so there are less losses in transit.

6.6. Graph theoretic properties

In the previous section, we provided several measurement results obtained from our testbed. We also evaluated our network in terms of several graph theoretic properties. We evaluated various network centrality measures such as degree distribution and betweenness. These evaluations also provide us with several interesting insights, and in some cases, complement the results obtained via measurement-based studies.

Fig. 18 shows the QuRinet site connections based on the node degrees of each site. The central nodes in the graph are the QuRinet sites that have the most connections in the network. Site 1 (Field Station), Site 2 (DFG Hill), and Site 6 (Burn Hill) have the highest node degrees. These three sites are all situated on top of hills, with the best line of sight to other sites.

Fig. 19 shows the degree distribution for QuRinet sites. We observed that all sites are connected to at least two
other sites in the network. This is important in terms of providing redundancy in the network. Even if the signal from one site is weak, a particular node can still maintain connectivity to rest of the network. There is one site with as many as 22 neighbors, while most nodes have degree between 2 and 13. The average degree per site was found to be 8.7.

Fig. 20 shows the CDF and histogram of the betweenness factor of the QuRiNet sites. The betweenness centrality of a node $i$ in a network is defined as the fraction of the network paths that pass through that node [15]. Thus, betweenness is a measure of how important a node is in a given network, in terms of how much information flows through that node. A high betweenness value means that the node is very important and is part of a large number of shortest paths. The graph shows that there are three sites that lie on almost all the shortest paths in the network.

The final graph property that we consider is the clustering coefficient or the network transitivity (Fig. 21). The clustering coefficient of a node is defined as the ratio of number of connections in the neighborhood of the node and the maximum number of connections that the node can have if it were fully connected. It is thus a measure of the redundancy in the network. It takes values between 0 and 1. A higher value means that even if a link between two nodes fails, these two nodes can still communicate via a third node. The average clustering coefficient for QuRiNet was found to be 0.58.

7. 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.

7.1. 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 such that 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.

---

Please cite this article in press as: D. Wu et al., QuRiNet: A wide-area wireless mesh testbed for research and experimental evaluations, Ad Hoc Netw. (2011), doi:10.1016/j.adhoc.2011.02.001
**Fig. 13.** Far Hill – Site 4 node to gateway performance.

**Fig. 14.** Decker Pond – Site 5 node to gateway performance.
Fig. 15. Fordyce Pond – Site 9 node to gateway performance.

Fig. 16. East Ashley – Site 18 node to gateway performance.
Fig. 17. Decker Buoy – Site 22 node to gateway performance.

(a) Day

(b) Week

(c) Month

Fig. 18. QuRiNet layout based on node degree.

Please cite this article in press as: D. Wu et al., QuRiNet: A wide-area wireless mesh testbed for research and experimental evaluations, Ad Hoc Netw. (2011), doi:10.1016/j.adhoc.2011.02.001
7.2. 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.

7.3. 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.
7.4. 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 from other sources. 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. One of the goals is to study the mobility traces and predict variations in the link layer and network layer metrics.

7.5. 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. Moreover, existing tools that were proposed for wired networks, suffer from various limitations when applied to wireless networks. They do not take into account the random access nature of wireless networks, varying link capacities, and the protocol specific features of IEEE 802.11 (such as rate-adaptation). As part of this study, we have 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.

7.6. 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 off-line. QuRiNet has a special logging functionality that minimizes traffic overhead [13]. We have also evaluated various techniques that enable us to perform efficient monitoring, while minimizing the impact on end user’s traffic [14].

7.7. Association control in wireless mesh networks

Mobile users with Wi-Fi equipped devices (PDAs, e-book readers, and others) have to choose from a multitude of available wireless access points at any given location. This is even more true with the widespread deployment of wireless mesh networks across universities and municipalities. We designed and evaluated a cross-layer association control scheme that utilizes bottleneck bandwidth as the design metric. The goal is to provide the end user with an up-to-date image of the network status, based on which, the user can make an intelligent decision regarding which wireless access point to associate with. Our results indicate that choosing the right access point vastly improves the end user’s performance, while also achieving load balancing in the mesh backhaul.

8. QuRiNet website

In designing this wireless mesh network, we included a public website: http://qurinet.cs.ucdavis.edu as a visualization and graphing tool. This website has an overview of the whole project, along with the research objectives. An interactive map is included for those that want to know more about the individual sites. Related publications are listed for more information about QuRiNet. In the near future, this website will contain graphs for analyzing the network statistics, and to cross reference with the environmental data.

9. Future plans

We have presented QuRiNet, an outdoor wireless mesh network. We have 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 IEEE 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 cross-layer 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.

Acknowledgments

Thanks and appreciations go to the folks at the UCD Natural Reserve System, especially Shane Waddell and Virginia Boucher for providing their time to build out the infrastructure. Thanks also go to our colleagues for using QuRiNet for their research. We thank Stephanie Liese for helping with the initial phase of this work. This research was supported in part by the National Science Foundation through the Grant CNS-0709264 and the Army Research Office through a MURI Grant W911NF-07-1-0318.

References


Daniel Wu is currently a Software Engineer (SiteReliability) at Google. He received his Ph.D. from the University of California, Davis in 2010. His research interests include monitoring and management of wireless mesh networks.

Prasant Mohapatra is currently the Tim Boucher Family Endowed Chair Professor and Chairman of the Department of Computer Science at the University of California, Davis. In the past, he has been on the faculty at Iowa State University and Michigan State University. He has also held Visiting Scientist positions at Intel Corporation, Fanasonic Technologies, Institute of Infocomm Research (I2R), Singapore, and National ICT Australia (NICTA). He has been a Visiting Professor at the University of Padova, Italy and Yonsei University, South Korea. He was/is on the editorial board of the IEEE Transactions on Computers, IEEE Transactions on Mobile Computing, IEEE Transactions on Parallel and Distributed Systems, ACM WINET, and Ad Hoc Networks. He has been on the program/organizational committees of several international conferences. He served as the Program Vice-Chair of INFOCOM 2004 and the Program Chair of SECON 2004, QShine 2006, and WoWMoM 2009. He has been a Guest Editor for IEEE Network, IEEE Transactions on Mobile Computing, IEEE Communications, IEEE Wireless Communications, and the IEEE Computer.

He received his doctoral degree from Penn State University in 1993, and received an Outstanding Engineering Alumni Award in 2008. He is a Fellow of the IEEE. His research interests are in the areas of wireless networks, sensor networks, Internet protocols, and QoS. His research has been funded through grants from the National Science Foundation, Department of Defense, Intel Corporation, Siemens, Panasonic Technologies, Hewlett Packard, Raytheon, and EMAC Corporation.