Quail Ridge Wireless Mesh Network: Experiences, Challenges and Findings

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Abstract— **Wireless Mesh Networks are becoming a popular alternative to extending the wireless LANs we use today. Low-cost incremental deployment and the lack of a wired infrastructure lends mesh networks to "last-mile" solutions for ISPs or simply to aid in increased coverage area. In addition, we find that mesh networks are appropriate for our work in establishing a communication infrastructure at the Quail Ridge Natural Reserve. In deploying a mesh network at Quail Ridge, we seek to assist ecological research in the area and provide a testbed for wireless mesh networks research in the future. We are interested in looking at pursuing novel techniques for routing, QoS provisioning and wireless monitoring and maintenance tools. This paper will describe our work in the Quail Ridge Mesh network. It will give the reader an overview of our current system, deployment status, and how this test-bed will benefit mesh networks research.**

I. Introduction

In the last few years, many researchers and high-profile companies have set their sights on deploying Wireless Mesh Networks (WMNs). Mesh networks are composed of two types of entities: mesh routers (wirelessly interconnected access points) and mesh clients. Selected access points, known as gateways, have a wired connection to the Internet.

Mesh connectivity significantly enhances network performance by providing fault tolerance and load balancing Wireless Mesh networks have seen increased deployments in the areas of broadband home networking and enterprise networking. In addition, they are also being deployed at the community and municipal level, for extended service provider coverage to end users, in areas which lack wired infrastructure. Wireless Mesh Networks have also found a new application in disaster affected areas and other places that need inexpensive and speedy deployment.

This paper will present our efforts in the installment of a Wireless Mesh Network at the Quail Ridge Natural Reserve. Quail Ridge is used for environmental research by the Department of Ecology at UC Davis and is part of the University of California Natural Reserve System (NRS). It is located off Highway 128, about twenty two miles west of Davis. Our work in the reserve will provide wireless coverage over 2,000 acres of hilly terrain in the face of various topological and technological challenges. This network will be utilized for ecological research to study the flora and fauna in the region. The network will mostly support audio and video applications and help in collecting data from the sensors deployed in the reserve. Additionally, the mesh network will also provide us with an excellent testbed for carrying out further research in this area. We have currently setup eleven nodes in the reserve. All the access points are dual radio and utilize multiple channels to achieve higher throughput. The network currently supports three video cameras and few audio sensors that are being used to study the wild life in the area.

The Quail Ridge Wireless Mesh Network has the following important research goals:

1) Provide an extended network coverage for researchers.
2) A testbed for exploring Layer 2 issues.
3) A testbed for new monitoring and maintenance tools.
4) A testbed for exploiting multiple channel advantages.

Fig. 1. Quail Ridge Reserve

II. Related Work

A few experimental test-beds have been implemented in the field of wireless mesh networks for the purpose of research. The MIT Roofnet project [1] has about 37 nodes spread over four square kilometers of urban area. It provides rates of less than 1 Mbps over three to four hops to end users. Their focus is on the effect of routing protocols, node density etc. on the network performance. The Hyacinth project [2] is aimed at solving the channel assignment and routing issues for multi-radio multi-channel mesh networks. They have implemented a small test-bed which has 10 nodesCheraddi et al [3] have implemented a test-bed with about 20 nodes and are working on multi-channel issues on mesh networks. The BWN-Mesh test-bed [4] consists of about 15 mesh routers spread across one floor of a building. They are testing the effects of router placement, mobility and other issues on the performance of the mesh network. The WINGs project [5] is aimed at seamlessly integrating the current internet multimedia applications with multi-hop ad-hoc wireless networks.

Some high-profile companies have also started taking deep interest in this area. Microsoft Research [6] has an ad-hoc routing based mesh network with about 20 nodes. Several companies such as Tropos [7], Strix Systems [8] and Firetide [9] have started deployment of municipal mesh networks in various cities.

Apart from these experimental test-beds and commercial installations, several community wireless mesh networks have also come up, such as the Seattle Wireless [10], the Digital Gangetic Plains project [11] and the TibTec Dharamshala wireless mesh community network [12]. These projects aim at evaluating performance of different applications on mesh networks and study the impact of different technologies such as multiple channels, directional antennas, etc.

Our test-bed at Quail Ridge is different from several existing implementations in terms of both its location and its usage. Unlike most of the current test-beds that are implemented in laboratory environment, our test-bed is in a natural wild life reserve, which gives us a better opportunity to understand the nuances of wireless networks, variations in signal strengths, placement of antennas etc. Due to the lack of power supply in the reserve, our access points run entirely on solar power, which sets us apart from most test-beds. This feature may be a viable option for developing countries lacking in proper power infrastructure. The area of Quail Ridge is also free from interference and noise from other electronic devices, which enables us to measure more accurate results.

III. Quail Ridge Overview

The Quail Ridge Reserve is maintained by the UC Davis Natural Reserve System (NRS). It is a 2,000 acre of wilderness with hilly terrain. It is open to researchers for studying the flora and fauna found in this region. This reserve has a diverse set of mammals, reptiles and birds. These include mountain lions, bears, snakes, and frogs.

A. Climate and Terrain

Part of the reason to have a Wireless Mesh Network in the Quail Ridge Reserve was to provide better connectivity to the researchers. The hilly terrain and overgrown vegetation makes repeated trips a tedious and unbearable task. Even though there are dirt roads, it still takes a better part of an hour to get to the farthest edges of the reserve. By setting up a mesh network in the reserve, the task of remotely collecting data will be much easier. The area witnesses heavy rainfall in the winter months, making on-site research an impossible task. Temperartures vary from very high to very low during winters and summers. Thus, remote monitoring and data collection is a very attractive option for the researchers.

B. Applications

The Wireless Mesh Network in Quail Ridge reserve will be a medium for a number of different applications. Currently, it is providing connectivity for three network cameras [13]. It is also used by university researchers for periodic ecological data collection. These include rain, wind, temperature and solar radiation measurements. Apart from the cameras, acoustic sensors have also been installed at Decker Pond and other sites, to monitor the movement patterns of certain wild life like frogs etc. Several undergraduate classes, such as those on using remote networks for ecological research are also utilizing this network.

IV. System Architecture

Currently our Wireless Mesh Network is in its early prototype stage. Our plan is to upgrade incrementally both the hardware and software as the need arises, rather than try to perfect everything in a test environment. There are two reasons for this. One, the network needs to be running so some of the researchers can start using it. Two, deploying wireless mesh networks is very suceptible to environmental changes, and must be monitored and upgraded when necessary.

A. Site Layout

As shown in Figure 2, we currently have eleven sites deployed and running at Quail Ridge, with about twenty sites being the final goal. The network can be easily expanded as per the need and usage. The sites that are currently deployed include the Field Station, DFG Hill (two nodes), Dan's Repeater, Dan's pond, Decker Pond, Far Hill Repeater, Far Pond, BLM Burn Ridge, Fordyce Repeater and Fordyce pond. We are in the process of deploying the rest of the network. Figure 2 is the physical layout of the APs at the reserve.

Figure 3 shows the network topology. Currently, the links are statically set for both channel and neighboring AP. In this phase of the project, we will try to determine the base performance without added modifications. Once all the testing for this phase is complete, we will move on to more advanced software tweaking at the MAC and Network layer.

In Figure 3, the APs are represented as circles. The filled circles represent the sites that are currently deployed, while the empty circles represent the sites that are in the process of being deployed. The numbers next to the links are the 802.11g channels used on that link. An arrow on an edge indicates a directional antenna connection. A link without an arrow means it is an omnidirectional antenna. The link between dfghill1 and dfghill2 is a wired link.

B. Equipment

1) Access Points: This testbed at Quail Ridge was built using the small Soekris [14] net4826 embedded devices, as shown in Figure 4. This device runs on a 266 Mhz 586 processor with 128MB SDRAM main memory and 64MB compact flash for the Operating System and other storage. They are optimized for wireless communications with dual Mini-PCI Type III sockets. They also contain one ethernet

AP	Status	Omni	Dir	Neighbor Count	Notes
fldstn	Active	0	1	1	Field Station
dfghill1	Active	0	1	2	co-located at DFG Hill
dfghill2	Active	1	1	4	co-located at DFG Hill
dkrpnd	Active	1	1	1	Decker Pond
danrptr	Active	1	0	1	Dan's Repeater
danpnd	Active	1	0	1	Dan's Pond
farhill	Active	1	1	3	Far Hill
farpnd	Active	1	0	1	Far Pond
fordycerptr	Active	1	1	2	Fordyce Repeater
fordycepnd	Active	1	0	1	Fordyce Pond
blmridge	Active	1	0	1	BLM Burn Ridge
dkrbuoy	Planned	-	-	1	Decker Buoy - on water

TABLE I

SUMMARY OF ACCESS POINTS (ACTIVE AND PLANNED)

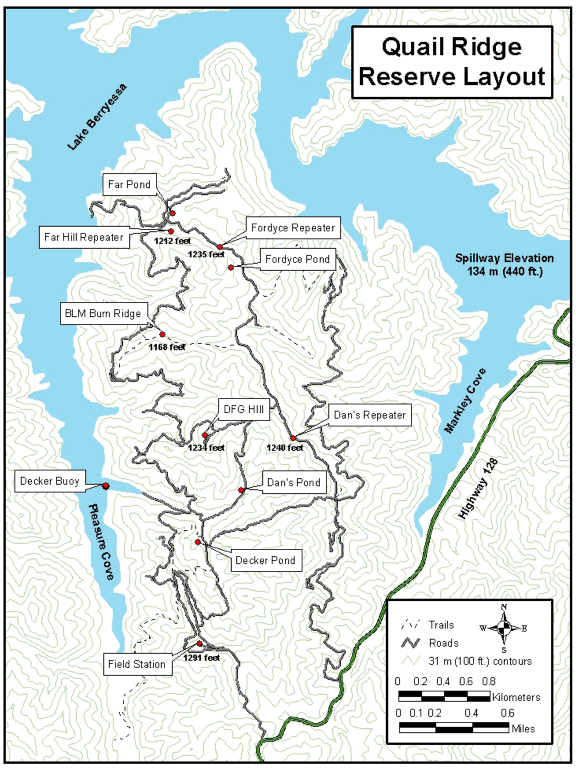

Fig. 2. Quail Ridge Reserve Network Site Layout

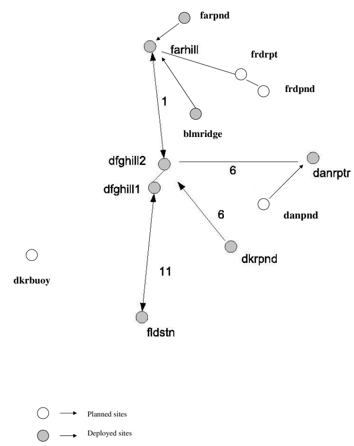

Fig. 3. Quail Ridge Reserve Network Logical Connections

Fig. 4. Soekris net4826, embedded device

interface and a serial interface. We selected the Ubiquiti Networks SuperRange2 802.11b/g 400mW High Power Atheros Wireless mini-PCI card as the wireless radios for our devices, keeping in mind the distances we must cover and the hilly forest covered terrain of the reserve.

These boards are driven by a custom built Linux distribution [15] using a 2.6 Linux Kernel. The kernel and filesystem are optimized for running on the embedded systems without sacrificing speed. We use the madwifi-ng driver from Madwifi.org [16] on our AP due to their level of programmability.

The mesh network has been set up using static IP addresses, with the various radios acting as access points or stations. Each Soekris board has two 802.11 b/g radios, but acts as a single node in the network. Linux Bridging is used to bind the multiple network interfaces (two wireless, one ethernet) to one IP address. Typically, a node will have one wireless interface that is attached to a directional antenna. This antenna will often connect to the backbone of the network, furthering communications back to the field station. In addition, a node often has an omnidirectional antenna attached to its other interface. This antenna can be used to supply wireless access to users in the vicinity, or it may be used to connect to the backbone as an alternative to the directional antenna.

Fig. 5. Node Setup at Decker Pond

2) Power Supply: As mentioned earlier, the Field Station at the Quail Ridge Reserve is the terminal point for all power and telephone lines. Due to the lack of power supply in the reserve, we decided to use solar power for the access points deployed at various sites. Each site has batteries with proper cabling installed. We have deployed one or more solar panels (figure 5) at each location, which charge the batteries to power the access points.

V. Experimental Data

Once we deployed part of the network, we decided to carry out some performance tests, and see how well our testbed is performing in face of various issues like hilly terrain, forest growth and long distances. This section will provide some preliminary results on the network utilization, RTT performance, signal strength and capacity of the network. These results will also help us in further developing the network by providing important information in terms of whether to use more directional antennas or omni-directional antennas, use of multiple channels and multiple radios etc.

A. System Capacity

Even though our gateway connection is limited to the fractional T1 line at the Field Station, we are still interested in the throughput and round trip time of the mesh network. Table II contains all the end-to-end throughputs in the system. These values are averaged from five bulk TCP runs of a minute each.

The highest throughput links are between dfghill1 and dfghill2 which is a wired link. As you can see, the throughput from fldstn to danrptr is not symmetric. Many of these links are not symmetric due to the environmental surroundings. Our network is currently achieving a throughput of about 15 Mbps over three hops and upto 20 Mbps over 2 hops. The hilly terrain and the forest growth are the primary reasons for signal degradation and lowering of throughput between two nodes.

Table III shows the average round trip time values corresponding to Table II. Data going to and from danrptr have very high RTT values. We attribute this high RTT value to the fact that the antenna used for the danrptr to dfghill2 link is weak and cannot achieve a high bit rate. This also makes the link have lower signal quality and have more packet errors.

B. Time Variations

The following figures are graphs of the Received Signal Strength Indication (RSSI) values in ten second intervals. RSSI is a way to measure the signal quality of the incoming signal. The RSSI values can range from 0 to 255 depending on the vendor. For Atheros chipsets, the value can range from 0 (weak to no signal) to 60 (very good signal). Figure 6 is a two-hour window during the middle of the day, while Figure 7 gives the same results for night. Notice the variations within each of the graphs. Every few seconds, we can notice the RSSI value fluctuating randomly.

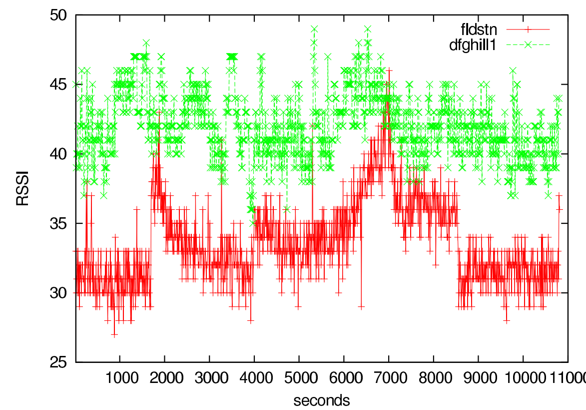

Fig. 6. RSSI values for signal quality over the fldstn-dfghill1 link (day time)

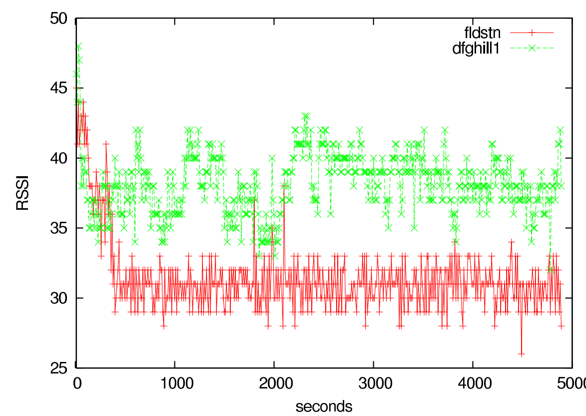

Fig. 7. RSSI values for signal quality over the fldstn-dfghill1 link (night)

Also, from the two graphs, we notice that the signal quality is much better during the day than at night. Notice also that the links are not symmetrical. The dfghill1 can receive the signal far better than the fldstn can at almost all points in time.

C. Network Utilization

Figure 8 is a graph of the utilization of the mesh network. The data was collected over a period of approximately an hour and a half at the dfghill site. This node was chosen because all

	Destination						
Source	fldstn	dfghill1	dfghill2	dkrpond	farhill	farpond	blmridge
fldstn	-	15.18	15.08	1.97	15.11	3	1.95
dfghill1	18.32	-	23	1.45	21	3.85	3.27
dfghill2	21.5	24.32	-	1.94	19.63	4.78	2.92
dkrpond	1.7	3.98	1.85	-	1.85	1.31	2.53
farhill	14.26	15.21	14.8	1.71	-	4.22	3.63
farpond	2.51	5.26	5.76	2.09	5.14	-	-
blmridge	1.75	3.1	3.05	2.44	4.18	-	-

TABLE II
END-TO-END THROUGHPUT MATRIX (IN MBPS)

	Destination						
Source	fldstn	dfghill1	dfghill2	dkrpond	farhill	farpond	blmridge
fldstn	-	48.37	47.82	309.7	36.94	224.75	304.63
dfghill1	47	-	23.15	152.56	36.98	138.4	215.63
dfghill2	35	25.44	-	230.64	30	111.28	202.5
dkrpond	402.1	349.15	390	-	390	789	532
farhill	37.05	32.28	32.63	475.4	-	151.7	395.2
farpond	241.18	107.45	106.15	502.2	274.2	-	-
blmridge	391.4	666	396	330.3	291.5	-	-

TABLE III
END-TO-END AVERAGE RTT MATRIX (IN MS)

traffic entering and leaving the network has to go through DFG Hill and thus it forms an ideal point for network utilization measurements.

As mentioned earlier, dfghill hosts one of the video cameras in our network. The test was carried out to see the network utilization when this camera is being used. The high throughput area in the graph corresponds to the time when the camera was being utilized, while at other times the throughput goes very low as there is no traffic in the network.

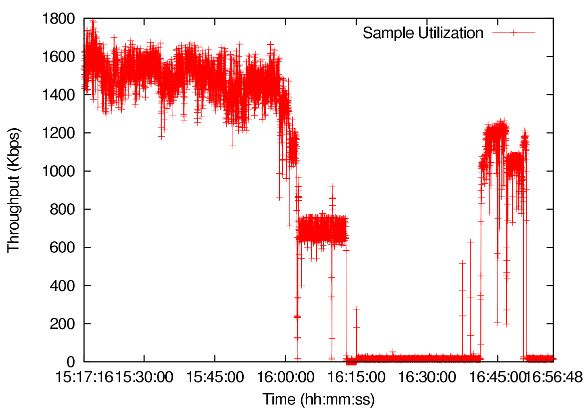

Fig. 8. 1.5 Hour Sample Utilization between fldstn and dfghill1

The second graph (figure 9) also shows the network utilization over a one hour period during the day. However, this time, both the cameras at dfghill and far hill were activated. The far hill camera is connected over three hops from the field station. The data collection point for the experiments was the dfghill1 access point as it is the last hop for all traffic bound for the gateway at field station from the mesh network. The network utilization was measured using a passive monitoring tool called COntinuous MOnitoring (CoMo). This tool [17] was ported to the access points used in the network. It enables us to take various measurements at different points in the network and log the data for later analysis.

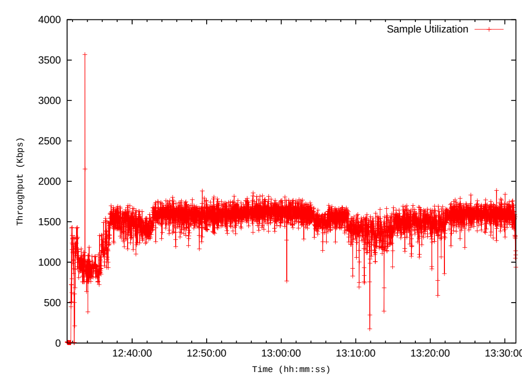

Fig. 9. 1 hour sample utilization between fldstn, dfghill and farhill

VI. CHALLENGES AND LESSONS LEARNED

The deployment of this network at Quail Ridge provided us with good insights and important knowledge regarding wireless mesh networks. It gave us an opportunity to test the various theoretical ideas and test their validity in the practical situation. We faced several challanges in the course of this project and learnt several important lessons.

One of the earlier issues we faced was that of the power level of the wireless cards. In our laboratory testbed, we were using 200 mW cards. However, in the actual setup at Quail Ridge, these cards proved to be of insufficient power to achieve high signal quality across large distances and hilly terrains. Thus, we decided to use cards with higher transmission power of about 400 mW. Their was a marked difference in the received signal strength with these cards.

However, the use of high-power cards alone was not sufficient to achieve good network performance. It was also required to use antennas. However, due to the geographical factors in our case, it was not sufficient to use omni-directional antennas. We noticed marked improvement in the signal quality and hence the data rate by using directional antennas, specially for the long haul links, such as that between the field station and dfghill and dfghill and far hill.

Along with the use of directional antennas, another important lesson to be learned was that of the placement of antennas. From our earlier experience [18], we had learnt that the placement of antennas is very important, even if they are on non-overlapping channels and are not supposed to interfere theoretically. For antennas with a gain of 5 dbi, the distance between them should be atleast three to four feet. Apart from the distance between the antennas, their elevation from the ground should also be sufficient to avoid signal degradation via ground interference. These challenges were found to be very much applicable to our deployment at Quail Ridge and the necessary steps were taken to avoid them.

Another important observation from this project was that the theoretical propositions regarding the performance of wireless mesh networks are far from what we see in the real scenario. We observed asymmetrical signal strengths and throughput values between the same two nodes. Even on the same link, there are large variations on signal strength and throughput at different points of time.

VII. Conclusion and Future Work

We have deployed a multi-channel multi-radio Wireless Mesh Network at Quail Ridge. The site of deployment is a 2,000 acre natural reserve, with hilly terrain and forest growth. Due to the unavailability of power lines, our network currently utilizes solar power to run many of the remote access points. Eleven of the sites are up and running. The mesh network also currently supports three video cameras and few audio sensors. The network is mainly utilized for ecological research and wild life monitoring. There are several small research projects as well as undergraduate class projects going on at Quail Ridge that utilize our network. We have tested the performance of the links in between the various access points and the signal quality of some of the links. We have found that signal quality varies over time and between the both ends of a link asymmetrically. Similar results were observed for the throughput measurements. We also ran some network utilization tests to study the amount of load on the network when the cameras are being used.

The network also provides us with an excellent testbed for future research in the area of wireless mesh networks. Future upgrades to this deployment will include a Layer 2 routing scheme, a scheduled MAC and new monitoring and maintenance tools. Another future goal involves obtaining measurement based inferences from the network. We plan to monitor the network to collect network statistics and analyze these to understand various aspects of a wireless mesh network such as variations in signal strength with time, how changes in weather, humidity, temperature etc. affect the signal strength and hence the network performance, effects of multiple channel and radios on network performance, network utilization, packet loss rate etc.

Acknowledgment

We would like to thank Shane Waddell and Virginia Boucher for their help in planning, designing and implementing this wireless mesh network. Without their help and support, we would not have been able to carry this project onwards.

Website

Readers are encouraged to visit [13] for further information regarding the status of the network at Quail Ridge and to use the cameras that have been deployed at different mesh nodes in the network. In the future, we also plan to facilitate remote performance monitoring of the various nodes in the network via the website.

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