ENABLING BROADBAND DATA ACCESS FOR THE DIGITAL WATERSHED WITH HETEROGENEOUS WIRELESS NETWORKS

Gayatri Venkatesh[1], Kuang-Ching Wang[2], and Christopher Post[3]

AUTHORS: [1]Graduate Student, Dept. of Electrical and Computer Engineering; [2]Assistant Professor, Dept. of Electrical and Computer Engineering; [3]Assistant Professor, Dept. of Forestry and Natural Resources, Clemson University, Clemson, SC 29634-0915.
REFERENCE: *Proceedings of the 2008 South Carolina Water Resources Conference*, held October 14-15, 2008, at the Charleston Area Event Center.

Abstract. The Digital Watershed project at Clemson University aims to develop a broadband wireless mesh network that facilitates aggregation of data from sensors distributed in the watersheds and relaying of their data streams for Internet access. Typical sites of monitoring interest for water resource management are in the wilderness with substantial foliage and hilly terrains that impede radio communication, posing unique challenges to maintain wireless network connectivity and achievable bandwidth. The paper presents two wireless mesh networks developed for the Issaqueena reservoir in the Clemson Forest and Hunnicut Creek watersheds, connecting water quality, temperature, and flow sensors amidst densely vegetated streams and hills. The mesh networks locally connect sensors in the field to a local aggregation gateway using IEEE 802.15.4 (Zigbee) radios; the gateway, in turn, connects to Internet through two alternative means using either a multi-hop long range IEEE 802.11a/g connection or a direct EDGE cellular connection. The study examines mesh network design considerations ranging from radio selection, placement, and configuration to cost, bandwidth, and reliability tradeoffs. The network enables further study on robust routing, radio and antenna adaptation, end-to-end bandwidth assessment and quality of service control for the Digital Watershed mesh networks.

INTRODUCTION

Effective water resource management depends critically on periodic and systematic monitoring of the water system. The increasing and competing demands for water have rendered it necessary for authorities to monitor the water income and withdrawal in real time to assure effective water usage. A comprehensive water management solution will require monitoring the watersheds throughout the state, country, or even across countries. To track water from its source to its estuaries, a large number of sensors must be deployed throughout each watershed, and the traditional repeated manual collection approach is clearly inadequate. With the advances in wireless sensor technologies, it is envisioned by many that future nature monitoring systems will widely utilize wireless sensors for long term monitoring and automated data reporting through a properly designed network infrastructure. Such a wireless sensor based system is expected to transfer the data to a centralized cyberinfrastructure that includes processing servers, storage, and visualization services, all connected by a capable network infrastructure built from a mixture of wireless and wired networking technologies.

There has been, however, limited work that has taken place to identify and solve the challenges in building wireless sensor networks in the wild. A number of wireless sensor networks have been built "near" forests, e.g., the Great Duck Island sensor network that monitors the environment for bird ecology study (Mainwaring et al., 2002), or the Redwood Macroscope sensor network that monitors the microclimate at different heights of a 70-meter tall redwood in California (Tolle, 2005). While these projects were constructed in forest environments, they have stayed close enough to the forest edge to establish line-of-sight wireless network connections for Internet access. The Digital Watershed project at Clemson University was tasked to develop a wireless network infrastructure for connecting pervasively deployed sensors along the state's rivers from their source waters to their estuaries. Given the aggressive goal, the project needed to push the wireless sensor network much deeper into the forest surrounded watersheds, such that sensors deployed anywhere in the watershed can continuously report their data reliably to Internet data servers without human intervention. To deploy sensors in large quantities and across large areas, wireless networks must be used, for the system to be economically feasible and environment friendly. Given the remote and wooded sensor locations, the wireless networks must be able to overcome long distances and potential foliage obstructions and still maintain an acceptable and reliable data transport capacity.

The Digital Watershed project identified four research sites with different environmental features and sensing requirements. This paper presents two networks built at, respectively, Lake Issaqueena in the Clemson Experimental Forest, and the Hunnicut Creek on our campus outskirt, both with creeks flowing through deep woods. To build the two networks, a combination of four types of network links were utilized: long range transit links, local mesh network links, steerable directional antenna links, and direct cellular links. The rest of the paper describes, respectively, the related work, network design, measurement studies, and a discussion on our future research directions.

BACKGROUND AND RELATED WORK

Wireless mesh networks have been widely used in metropolitans to provide wide area wireless network coverage at low cost and setup time. Such networks are composed of a group of base stations interconnected with wireless links in a mesh topology, while each base station provides wireless connectivity to a few client devices. MIT Roofnet (Aguayo et al., 2003) was one early example with 20 Wi-Fi routers (with omni-directional antennas) providing wireless coverage to mobile users (laptops with Wi-Fi radios) across a good part of Cambridge, MA. Only a subset of the 20 base stations had wired Internet connectivity; mobile users connected to unwired base stations would have their Internet traffic relayed by multiple base stations to reach a wired one. Since not all base stations require a wired Internet connection, mesh networks reduce the cost and time required to deploy a wide area network infrastructure. Furthermore, since all base stations that can receive each other's wireless transmissions are essentially interconnected, a mesh network provides mobile users with more robust end-to-end connectivity even if some or all of the wireless links among base stations can occasionally be down or face high chances of packet errors. Similarly, the VillageNet project (Dutta et al., 2007) used low cost Wi-Fi routers and high gain directional antennas to create a mesh network connecting multiple villages in rural India. These projects and many others alike have mostly dealt with line-of-sight or minor obstruction among the mesh network nodes.

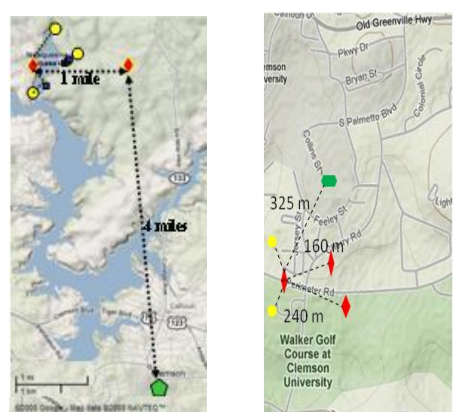
To deploy mesh networks around a forest setting, the key question to be considered is whether the wireless links can operate reliably with the needed data capacity. A number of studies have reported the Wi-Fi network link performance over short (Liese et al., 2006) and long distances (Ireland et al., 2007), concluding the significant impact of antenna orientation, interference, and received signal strength. The recent Quail Ridge Reserve project at UC Davis (Wu et al., 2007) is in the closest context with our Digital Watershed network, as it builds a mesh of Wi-Fi radios spanning the hilly and wooded reserve area for supporting ecology research and communication; the network by far places all radios on towers to maintain line of sights to their neighbors.

NETWORK DESIGN

The Digital Watershed project's objective is to explore a systematic strategy to deploy state wide watershed sensing systems; hence, the first step to designing the networks for both the Clemson Forest and Hunnicut Creek sites is to define their common network architecture. First, it was identified that the majority of watershed sensing networks would be located at locations far from existing Internet gateways (wired gateways or cellular towers), from a few miles to tens of miles. Second, it was identified that the majority of sensing sites can be distributed in densely wooded areas where: i) seasonal foliage change and animal activities can impact the reliable connection of wireless links inside the woods, and ii) the area to be monitored is not only vast but also requires preservation of their original state. Thus, the network must compose of two key components:

1. *long range transit links* that establish connectivity from an Internet gateway *to* the watershed vicinity, either the edge or the center of the watershed area;
2. *local mesh network links* that establish reliable mesh connectivity among sensors *in* the watershed in spite of dynamic link conditions.

It is considered that the Internet end of the long range transit link will be at a facility with wall power, while the watershed end will be powered with batteries attached to solar panels. The local mesh links are inside the watershed and almost certainly have no wall power and must utilize batteries with solar panels. Due to the power source assumptions, the long range transit link can flexibly leverage high power transmissions with high gain antennas to optimize its data capacity. The local mesh links, however, should be power conserving and transmit at only a power that is justified necessary. Measurement studies reported in the later sections will study the tradeoff of power and throughput of both types of connections. The long range links can utilize more than one pair of relay radios (referred to as transit bridges) based on the distance to the site and the availability of line of sights, noting that long distance transmissions are very susceptible to obstacles. On the other hand, mesh links typically connect sensors in short distances. Figure 1 shows the terrain map and network topology for the Clemson Forest and Hunnicut Creek networks with Internet gateways shown in green, transit nodes



(a) (b)

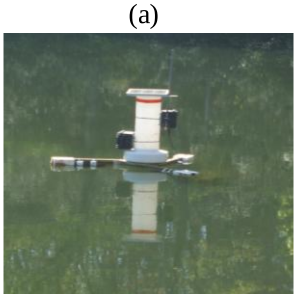
Figure 1. Network topology at (a) Clemson Forest (b) Hunnicut Creek. Green marks locate the Internet gateways, red marks are transit bridges, and yellow marks show local sensor groups.

in red, and sensor groups in yellow. Each sensor group consists of wireless sensors, relay radios, and mesh routers, and the entire group interfaces with the transit link through a gateway.

Multiple wireless radios were adopted in the network. The sensors and relays utilize IEEE 802.15.4 (Digi XbeePro) radios, the mesh routers have dual IEEE 802.15.4 and IEEE 802.11b/g (Linksys WRT54GL) radios, and the transit links utilize IEEE 802.11 b/g (Cisco 1310) and IEEE 802.11a (Cisco 1410) radios. At the Hunnicut Creek, a mesh router with a software steerable directional phased array antenna (Fidelity Comtech Phocus system) was used as the gateway, such that it can connect multiple isolated sensing sites to be added in the future. While it is expected that the majority of rural watersheds will not have cellular radio coverage, the two research sites do have cellular coverage. The network equipped a few sensors with AT&T EDGE cellular modems (Digi ConnectWAN) that directly transmit data through the cellular base station to Internet, demonstrating an alternative method for low rate (up to 384 Kbps) sensors in urban and suburban segments of a watershed. The higher cost and rate limitations make it inappropriate for supporting video and audio streaming based applications.


(a)


(b)


(c)

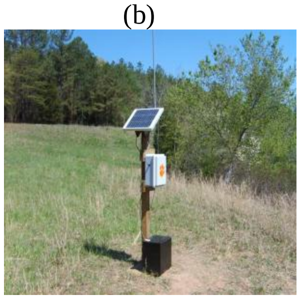

(d)

Figure 2. Local mesh networks connect sensors in forest; (a) inflow Aquarod sensor, (b) outflow sensor, (c) temperature sensor on buoy, and (d) lake side mesh network gateway.


(a)


(b)


(c)

Figure 3. Long range transit bridges at (a) Lake Issaqueena, (b) fire tower, and (c) Byrnes Hall rooftop.

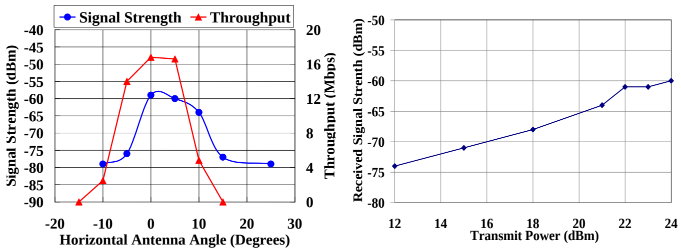
The long range transit network from campus to the Clemson Forest consists of two line-of-sight connections. The first link is 1 mile long between the lake (at the center of the forest) and the fire tower (on edge of the forest). The second link is 4 miles long between the tower and the rooftop of Byrnes Residence Hall on campus. As the lake-to-tower link must overcome a ridge of tall pine trees, IEEE 802.11b/g radios were chosen for its theoretically better (than IEEE 802.11a) penetration ability at its 2.4 GHz radio band. The campus-to-tower link faces downtown Clemson that has a plethora of 2.4 GHz public access points which substantially raised the noise floor in the band; therefore, 5.8 GHz IEEE 802.11a radios were chosen instead. All transit bridges utilized high gain (21~22.5 dBi) directional antennas. Figure 3 shows all deployed transit bridges.

MEASUREMENT STUDIES

Measurement studies on achievable data throughput and other potential factors impacting performance were conducted on the two networks. The following presents the measured results according to three link types.

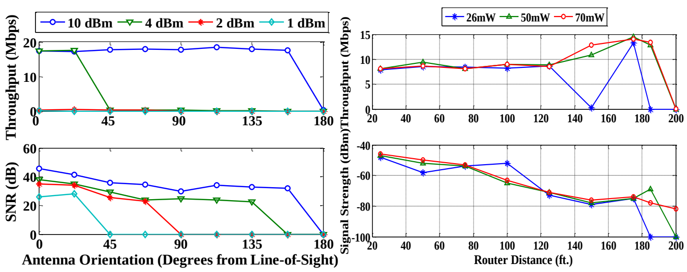
Long Range Transit Link: On the campus-to-tower link, it was observed that the signal strength increased with the transmit power while the throughput remained insensitive to the transmit power changes (Figure 4). The link was able to maintain connection with the campus antenna rotated within a 35 degree range and the tower antenna fixed, though the throughput varied from 4 to 13 Mbps.

Medium Range Directional Antenna Link: The Fidelity Comtech routers with software steerable directional antenna can potentially be used as a long range transit bridge or a short-to-medium range mesh router in the forest. With two of them placed 525 ft apart on an empty parking lot, and an antenna beam width of 35° vertical and 43° horizontal, the achievable throughput was measured with the two antennas



(a) (b)

Figure 4. Long range link's (a) throughput and signal strength at 24 dBm transmit power; (b) signal strength at 7 power levels.



(a) (b)

Figure 5. (a) Throughput and SNR for short range directional link; (b) throughput and signal strength for tree-obstructed link.

from perfectly aligned (0° line of sight) to facing away (180°) in 22.5° steps at different transmit powers. It was seen that the valid range for connection depended sensitively on transmit power, while throughput remained stable whenever the link was connected (Figure 5(a)).

Tree-obstructed Omni-directional Link: Linksys routers with its factory default omni-directional antennas were placed in a wooded area with approximately uniformly grown trees (bigger trees per 8 ft and thinner trees per 3 ft). It was found that the received signal strength decreased consistently with distance but the throughput variation was rather unexpected. Throughput remained steady for over 120 ft and had an unexpected rise afterwards before losing connectivity. The cause of the rise remains to be confirmed. Increasing transmit power did not increase the received signal strength and throughput in this environment.

CONCLUSION

This paper gave an overview of the architecture and prototype implementation of the wireless networks in the Clemson Digital Watershed project using multiple types of wireless networking technologies, along with the results from measurement studies conducted over the networks. The measurement studies showed that i) the long range line-of-sight link stayed connected for about 35° with a throughput insensitive to transmit power changes; ii) the range of the directional antenna link's connection depended sensitively on the transmit power while throughput remained stable when connected; iii) Effect of vegetation obstruction on the signal strength was consistent but that on the throughput was unexpected.

The project will continue to study the necessary components for a scalable, reliable, and quality assured watershed sensing system. Specifically, the performance assessment methods studied in this paper will be used to develop a network quality assessment methodology for the network, with which robust network management and quality of service control methods can be realized.

ACKNOWLEDGEMENT

The authors acknowledge the support from the Clemson PSA Digital Watershed/Intelligent River Project, Clemson Computing & Information Technology, Clemson Research Investment Fund, Cisco Systems for sponsoring the long range wireless bridges, Clemson Forest, graduate students Sajindra Pradhananga, Sandeep Lokala, Michael Frye, Rahul Amin, Michael Juang, and SC Governor School students Shari Carter, Jason Isenhower, and James Vaughn.

LITERATURE CITED

Aguayo, D., et. al., 2003. MIT Roofnet. In: Proc. of ACM Mobicom'03, pp.1-2.

Dutta, P., et al., 2007. VillageNet: A low-cost, 802.11-based mesh network for rural regions. In: Proc. of COMSWARE'07, pp.1-8.

Ireland, T., et al., 2007. The impact of directional antenna orientation, spacing, and channel separation on long-distance multi-hop 802.11g networks: A measurement study. In: Proc. of WiOpt'07, pp. 1-6.

Liese, S., et al., 2006. Experimental characterization of 802.11b wireless mesh network. In: Proc. of IWCMC'06, pp. 1-11.

Mainwaring, A., et al., 2002. Wireless sensor networks for habitat monitoring. In: Proc. of WSNA'02, pp.1-10.

Tolle, G., et al., 2005. A macroscope in the Redwoods. In: Proc. of ACM SenSys'05, pp. 51-63.

Wu, D., et al., 2007. Quail Ridge wireless mesh network: Experiences,Challenges and Findings. In: Proc. of TridentCom'07, pp.1-6.