Mesh Networking

Deploying Rural Community Wireless Mesh Networks

Inadequate Internet access is widening the digital divide between town and countryside, degrading both social communication and business advancements in rural areas. Wireless mesh networking can provide an excellent framework for delivering broadband services to such areas. With this in mind, Lancaster University deployed a WMN in the rural village of Wray over a three-year period, providing the community with Internet service that exceeds many urban offerings. The project gave researchers a real-world testbed for exploring the technical and social issues entailed in deploying WMNs in the heart of a small community.

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Wireless mesh networks (WMNs) create a resilient infrastructure using a combination of wireless networking technology and ad hoc routing protocols, which together let service providers or communities establish networks in places without prior groundwork. A WMN is a self-managing network in which all nodes act as routers that can route traffic either directly or via a multihop path.[1] The system is dynamic; it can adapt to nodes entering the network or those exiting it due to node failure, poor connectivity, and so forth. Mesh networking's robust nature makes it an ideal technology to use in rural villages in which establishing a wired network would be overly complex.

In early 2003, residents of Wray, a small village community, approached Lancaster University in search of a solution to help it achieve broadband Internet access. Wray is situated approximately 10 miles from Lancaster in northwest England. Villagers felt that the unavailability of broadband was jeopardizing local businesses, education, and the overall community itself. The university and community members thus initiated a collaboration to deploy WMN technology throughout the village. In addition to giving villagers broadband access for the first time, the project gave university researchers a chance to investigate the processes and technical challenges associated with a mesh network's real-world deployment and operation.

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Wray's situation isn't uncommon, even in today's Internet age; while urban areas receive Internet connectivity with ever-increasing bandwidth, rural areas are largely left behind, often with only dial-up modem alternatives. As technological advances lead to a wider use of Internet communication for social activities, such as television content and telephony, the digital divide becomes more and more apparent. Our research at Wray investigates alternatives for rural communities that continue to suffer a lack of suitable broadband services. Here, we discuss a range of deployment and operational issues based on three years' experience of running Wray's mesh network. In addition to highlighting initial deployment challenges, we detail various technical challenges that we had to overcome to ensure the service's continued success. Finally, we describe the network's positive impact on the villagers and local businesses.

Figure 1. Aerial photograph of Wray village. The village is approximately two square kilometers, with houses located along two main streets. The school, located on the south side, provides the village's initial 10-Mbyte broadband feed, delivered via a 5.8-GHz radio link.

The Wray WMN

Figure 1 shows an aerial photograph of Wray village taken from the west. The village covers approximately two square kilometers. The village school is located on the south side, with the public house in the northwest and most homes located on two main streets.

The WMN we deployed in Wray consists primarily of LocustWorld mesh nodes,[2] which we placed strategically throughout the village. The WMN backbone operates using IEEE 802.11b network technology, with the Ad-Hoc On-Demand Distance Vector (AODV) protocol[3] providing routing to the network backhaul — a 5.8-GHz wireless radio link accessed from the local school. Clients connect to the Internet wirelessly via one of the mesh nodes using off-the-shelf IEEE 802.11b network cards.

Network Deployment

Initially, the only choice for internetwork connectivity to the village was satellite, dial-up, or the school's radio link connection (all schools in the region have access to broadband through a government-funded initiative). We decided that the radio connection could carry both interactive and high-bandwidth services. Also, because the school was on a hill, the signal could propagate across the village to households relatively easily, although other hills, tall buildings, and large trees created several blind spots. To reach the blind spots, we had to navigate around the obstacles using multihop links.

We placed wireless mesh nodes in strategic village locations determined by geography and projected usage. Individual nodes used an externally mounted omnidirectional antenna to distribute the signal locally and to provide connectivity to the village school for the Internet uplink. For redundancy, we placed three mesh nodes at the school (each with a directional antenna).

In the weeks following the initial deployment, we observed unexpected behavior, including unreliable connectivity at the Community Hall. There were also several blind spots within the village that experienced poor signal levels, leading to intermittent connectivity and high latency. After further investigation, we found that residents positioned the aerials too low or mounted them too close to existing television aerials (and thus experienced signal-propagation problems). Our general solution was to install additional mesh nodes into poor coverage locations and increase the existing aerials' height to improve overall network stability and coverage area.

Figure 2 shows the Wray WMN's current network topology and coverage area. We continue to adapt the topology as the network's requirements and demands change over time. Network configuration changes are often due to interference from consumer equipment (such as video senders). Additionally, multipath propagation (whereby signals reach the receiver by two or more paths) is particularly problematic during the summer months when radio signals reflect

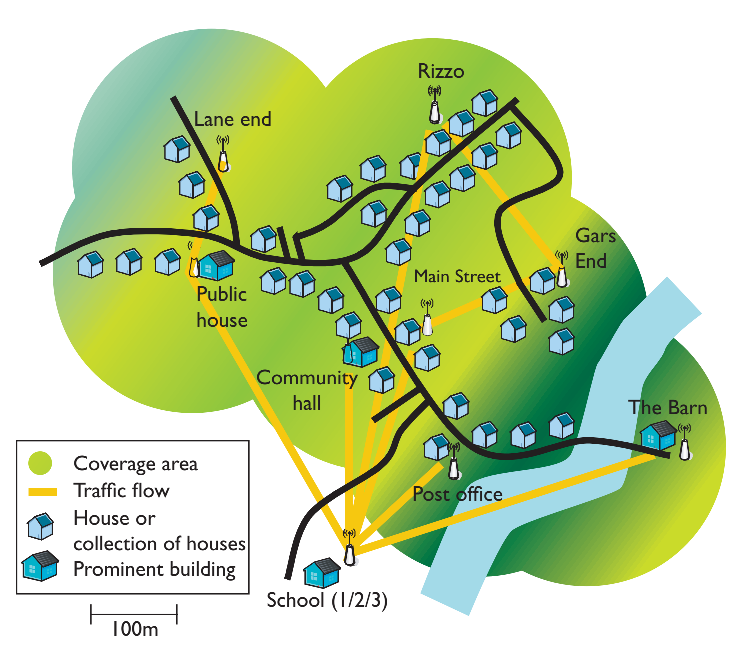

Figure 2. The Wray network's topology and coverage area. The topology changes over time, often due to interference from consumer equipment. Also, in summer months, radio signals reflecting off foliage can degrade connectivity for some users.

off foliage. This leads to degraded connectivity for some users.

Mesh Node Hardware and Administration

We chose LocustWorld mesh nodes, an off-the-shelf platform, because it lets community members actively participate in network deployment by purchasing and installing their own devices. It will also let the village continue to support and expand the network if our university ends its involvement with the project.

The LocustWorld nodes act as both routers (for cross-mesh traffic) and access points (for clients). They use a limited version of the Linux Slackware OS, which contains our key networking components, user diagnostic tools, and a kernel module to provide routing capability. The mesh nodes' wireless Ethernet adapter is a standard 802.11b wireless device with an externally mountable aerial. Aside from the school's three aerials, all other network aerials are omnidirectional. We achieve configuration and management using a series of scripts that modify internal configuration files. The scripts receive a list of configuration options from the Wireless Internet Assigned Numbers Authority portal, which provides a Web-based interface for the network's administration and control.

Early on, we realized that a minority of users might exploit the peer-to-peer file-sharing services to download large amounts of data. Originally, the mesh configuration would let a single user consume all available bandwidth for significant time periods, thus reducing the network's performance for other users. To obtain more detailed information about network utilization, we developed our own monitoring system. It captures information such as details of the individual flows through each node, the amount of latency to gateways, and path selection through the mesh network. We use this data to analyze overall usage patterns and highlight heavy users. Our monitoring system is particularly useful in isolating specific problems related to individual users or traffic types.

A range of off-the-shelf wireless network adapters connected households (clients) to the mesh network; the adapters' performance varied widely. Local community members typically used devices such as USB wireless network cards, which were mixed in their ability to connect to the mesh network. Users were often overly optimistic, expecting to connect to the network from anywhere inside their property without needing an external antenna. Not surprisingly, in all cases, using an external omnidirectional aerial provided reliable connectivity but also significantly increased installation costs. Furthermore, we found that the length of coaxial cable between the external antenna and the indoor wireless network adapter was extremely significant: users often experienced a high degree of loss across this cable. To overcome this, we employed a bridging device, using a short coaxial cable to connect to the external antenna, and traditional CAT5 cabling to connect to the user's PC.

For decentralized routing, we used the AODV routing algorithm, which was common on mobile WMNs. It's also a good choice on a static WMN because mesh nodes are located in users' homes. Because users can disrupt and unplug nodes at will, we consider the home a hostile environment. As such, we prefer a reactive protocol.

During normal network operations, we observed that nodes with relatively poor connectivity were particularly susceptible to noise from other transmitting nodes. Although such nodes could successfully transfer data over a single-hop, poor-quality link, they could do so

Related Work in Wireless Mesh Networks

Wireless mesh network (WMN) research is active across several domains, from modifications of the medium access-control layer to the application layer. Several industrial standards groups — such as IEEE 802.11s — are actively working on mesh networking specifications. In addition, many organizations are operating live WMNs as research testbeds. However, these efforts often focus on specific research aims, rather than on actual service provision as in our Wray village project.

University Testbeds

One of the earliest research mesh networks was Carnegie-Mellon University's mobile ad hoc network testbed, which consisted of seven nodes (two stationary and five mobile).[1] Routing was performed using dynamic source routing,[2] which also integrated the network to the Internet gateway. The researchers' aim was to examine the network's behavior under varying traffic conditions, but the network lacked self-management and cognitive configuration. They deployed the network within the university, rather than in a real-world environment, and used it only for testing purposes.

The University of California, Santa Barbara, also established a campus-based mesh testbed,[3] which consists of 25 nodes located throughout a five-story campus building. Routing is performed using the Ad-Hoc On-Demand Distance Vector protocol.[4] Each node consists of multiple wireless radios and two Linksys WRT54G devices, one acting as the AODV router and the other for out-of-band AODV mesh node management.

Community and Industry Projects

In San Francisco, the Meraki "Free the Net" project (http://meraki.com/about/freethenet) provides mesh connectivity through community individuals who host inexpensive custom hardware across the city. The project built the mesh framework using ideas from MIT's much earlier Roofnet testbed — which is similar to Humboldt University's Berlin Roofnet project — and aims to improve WMNs' community aspects.[5] The project functionality is provided using a distributed hash table to enable the distributed Dynamic Host Configuration Protocol, domain name service, and Address Resolution Protocol. Because each network node provides its own services, the project provides seamless roaming between mesh nodes and a more robust failover system. It also lets administrators modify the network without significantly impacting clients. Although students are implementing the testbed within the university, the scenario isn't applicable to situations such as Wray because students and staff have a wide range of Internet connectivity options, and the setting lacks the real-world complications of rural village life.

Several research groups have investigated mesh networking from an industrial perspective. Microsoft Research (http://research.microsoft.com/mesh) has created a loadable Windows driver — the mesh connectivity layer — that lets developers create ad hoc networks using a modified version of the Dynamic Source Routing Protocol. Other examples include Nortel, which has rolled out a series of carrier-class WMN products, and Kiyon (www.kiyon.com), which has created automated mesh networks for small and home offices.

Unlike our work, however, all of these projects focus on a specific study area rather than on examining a mesh network in a real-world context that highlights how WMNs function when under real constraints in rural communities.

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only if there were no other transmissions in the area. If a second node within range of the poor-quality link begins to transmit, the original node's link would fail and thus increase overall latency across the mesh. To reduce the use of poor-quality links, we set a lower bound for the mesh nodes' minimum signal strength – thus effectively forcing the mesh to use multiple hops rather than a single hop. This decreased latency across the mesh, but also impacted the network's available redundancy (and individual nodes' maximum throughput).

Quality of Service

Providing quality of service (QoS) over a wireless medium is particularly challenging.[4] Given that the transmission medium is a license-free band, there are no guarantees that the medium will be clear when users attempt a transmission. We readily observed this when two or more mesh nodes within the same transmission area attempted to simultaneously use the network for large downloads; in such cases, latency increased dramatically.

To ensure that no single device (or user)

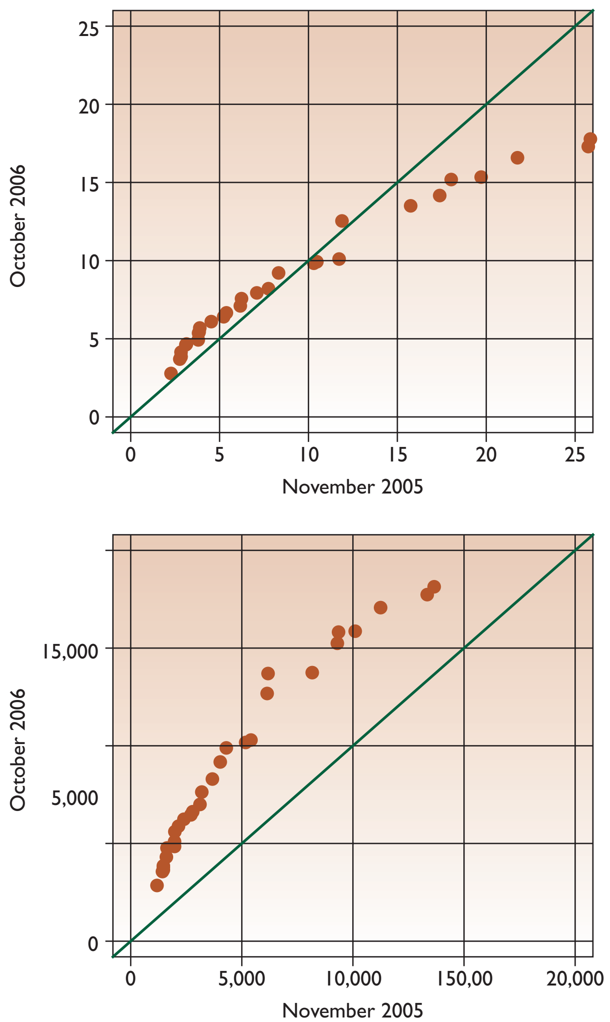

Figure 3. Differences in mean per-node load (top) and aggregate network utilization (bottom) after one year of network deployment.

could exploit all available bandwidth, we placed simple bandwidth restrictions on both end users and each individual mesh node. The restrictions use a leaky-bucket traffic-shaping algorithm to control the network's data-injection rate. The algorithm shapes traffic into a steady stream to the network, as opposed to erratic bursts of low- and high-volume traffic flows. We consider these restrictions temporary, and will revoke them once QoS mechanisms are readily available for wireless networks.

Technical Evaluation

The Wray WMN has been operating for almost two years and has undergone several significant changes. In particular, we've expanded the network to accommodate increasing numbers of users — doubling the number of mesh nodes in the village — and introduced configuration changes to ensure fair network use among all connected households. We now highlight a few particular issues that arose during deployment and discuss how the overall community has evolved as a result of broadband availability.

Self-Organization and Configuration

Ian F. Akyildiz described WMNs as "dynamically self-organized and self-configured,"[1] leading us to assume that network deployment would be trivial. This turned out to be a misconception for the current generation of WMNs, due both to hardware- and software-related issues and a lack of unification among them.

Current WMN radio hardware physically restricts the device connectivity's range (power) and conditions (noise/multipath fading), resulting in poor or no connectivity for unplanned deployments. Even with planned deployments, poor software decisions can aggravate the wireless radio device's behavior. For example, LocustWorld's WMN implementation fails to balance gateway selection based on parameters such as available bandwidth or connection quality; instead, it selects the first available gateway. In addition, as we described earlier, gateway selection doesn't consider AODV path selection, which in turn fails to consider radio-connection quality. This lack of component unification leads to erratic behavior, contradicting the WMN self-organizing ethos. As a result, we had to manually configure our network and consequently lost some of its dynamic properties.

Network Performance

We used our custom monitoring system to evaluate the traffic performance trends and the users' network usage patterns throughout the WMN's development and continued operation. We've collected a wide variety of performance data at a 60-second granularity since November 2005. For each mesh node, we recorded, compressed, and archived statistics — including flow activity, intramesh round-trip time (RTT), AODV state parameters, wireless coverage, and signal strength. We indicatively analyzed a subset of those statistics to show how adequate engineering and network provisioning produced acceptable service levels.

Figure 3 shows the quantile-quantile plots of

Table 1. Daily mean meshbox load (Kbytes per second).

Month	Minimum	Median	Mean	Maximum
November 2005	2.27	6.2	9.14	25.86
October 2006	2.78	8.28	8.68	17.77

Table 2. Daily aggregate mesh utilization (Gbytes).

Month	Minimum	Median	Mean	Maximum
November 2005	1.18	3.16	4.75	13.66
October 2006	2.86	7.34	9.0	18.14

the mean mesh node load (in Kbytes per second) and aggregate network use (in Mbytes) between November 2005 and October 2006. We computed these metrics by aggregating all active flows on a daily basis during each month. We plotted the 45-degree reference line to show the distributional similarities between each period's usage patterns. The upper plot shows that each node's average daily load doesn't assume a common distribution between November 2005 and October 2006. Although lower values seem to have increased slightly during the deployment's first year, it's evident that for larger values, per-node load has significantly decreased — by up to 32.4 percent. This is particularly important when compared to the lower plot, which shows the massive increase in aggregate network use. Daily usage has consistently grown by up to 55 percent, reaching 18.14 Gbytes (as evident in the quantile points' large departure from the reference line). Hence, network provisioning has resulted in a lightly loaded topology, even though daily network use increased by up to a factor of two in some cases. Tables 1 and 2 show summary statistics for per-node load and aggregate network utilization, respectively.

Figure 4 is a radar plot of the minimum, mean, and maximum RTT experienced by periodic "ping" polls during October 2006. Each plot point shows the monthly average of minimum, mean, and maximum RTT between each node and the network gateway. The radar successfully demonstrates RTT variations among different nodes deployed throughout the village. Most important, it graphically illustrates the overall, network-wide relationship among the three RTT quantities.

The fact that minimum, mean, and maximum RTT have the same relative differences across the mesh nodes reinforces our claim of adequate network provisioning and light per-node load. Measurements based on the Internet Control Message Protocol can be misleading in inferring overall network performance if ICMP packets are not treated identically with the rest of the network traffic. However, large fluctuations in relative differences between each node's three RTT quantities would indicate that certain paths consistently operate under higher load than others, regardless of their physical connectivity characteristics. Minimum RTT provides an approximation of the delay attributed only to the medium's propagation and transmission times, whereas mean and maximum RTT also encapsulate the network's load (queuing). As the radar plot shows, the differences in RTTs among mesh nodes are preserved for minimum, mean, and maximum values. Indeed, we've verified that these RTT differences reflect variations in signal strength among the different mesh boxes.

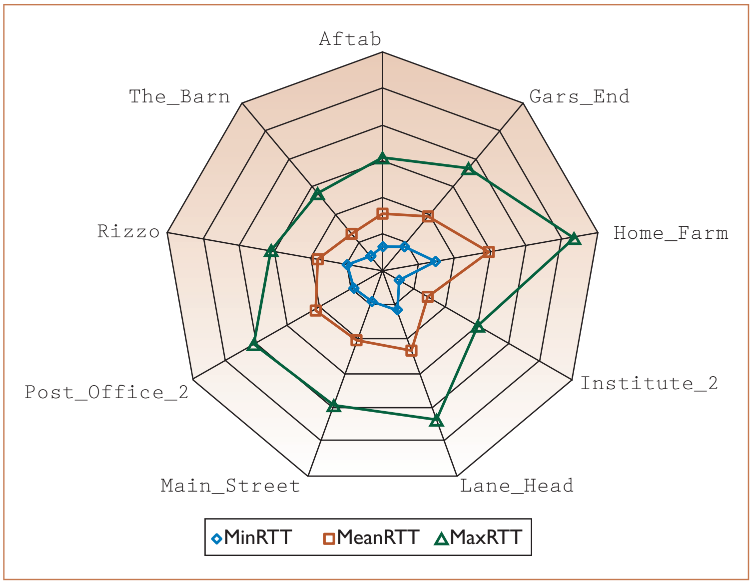

Figure 4. Summary of round-trip time (RTT) for each mesh node in October 2006.

Table 3. Network-wide round-trip time (RTT) for October 2006.			
Monthly RTTS (milliseconds)	Minimum	Mean	Maximum
Minimum RTT	10.31	17.88	29.02
Mean RTT	26.66	39.03	58.99
Maximum RTT	55.95	74.48	106.30

Table 3 shows summary statistics for the three RTT quantities.

Social Impact

Although our research focused on overcoming the technical challenges of deploying a rural community WMN, the three-year deployment also revealed significant social benefits.

User Impact

During the first few months of deployment, network usage patterns changed from relatively light traffic to long-lived, high-bandwidth flows. Our community survey clearly showed that peer-to-peer applications had quickly replaced email communication as the primary network activity. This trend had an increasing negative impact on network performance. Given this, we considered three general options: reeducating users, redesigning the network, or imposing strict traffic restrictions (< 0.5 Mbits per second, per user). Because the latter two options would result in the network not being used to its full potential, our only viable solution was to educate the community into changing its usage patterns.

We implemented an acceptable-usage policy stipulating that users shouldn't download large files (> 100 Mbytes) between 9 a.m. and 9 p.m. As users adopted this strategy, peak-time latency decreased and speeds increased. The strategy's success relied on the community's closeness, which made it easier to spread information about improving the overall service.

Management Issues

Many success stories are associated with introducing broadband into Wray. However, users have also raised a few concerns related to the use of peer-to-peer applications and the increased virus threat resulting from insecure (operating) systems. To address this, we educated users on end-system security technologies and on the implications of unauthorized use of copyrighted material.

The network administration and maintenance required is now minimal because the mesh's underlying logic successfully caters to operational anomalies — including hardware outages — and reroutes traffic as appropriate.

Communication and Community Awareness

The village is using technologies such as VoIP, email, instant messaging, and blogging to support social communication within the community and raise the village's profile in the wider region. Online communication has enabled residents in outlying farms to regularly participate in meetings. We've observed an increase in physical meetings among villagers to discuss network-related issues. Some villagers are also using Web cameras to keep an eye on elderly relatives.

Rural Businesses

Broadband connectivity has enabled Wray's farming community to remain competitive within a highly aggressive market. For example, farmers now use IT to register newborn calves online, which saves paperwork, postage, and (most crucially) time. Also, the use of e-commerce Web sites has transformed some local stores into international businesses.

The Wray network demonstrates how WMN technology can provide an alternative to a wired network infrastructure, offering rural communities broadband service that exceeds many urban offerings. It also provides a real-world mesh networking testbed for the research community. So far, our focus has been to maintain high throughput and low latency to facilitate interactive services such as VoIP. Alongside this, we're continuing research into scalable infrastructure provisioning in which components interact to improve WMNs' cognitive aspect.

Ultimately, any village-based WMN's long-term success requires a strong team to sustain and drive the network forward from the heart of the local community. We are able to achieve this through close contact, involving community members in all aspects of the project's design and implementation. With our successful initiative as a catalyst, Wray villagers are now using their knowledge and experience to help neighboring villages establish their own WMN infrastructures and thus take advantage of the far-reaching opportunities that broadband offers.

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