Deploying Rural Community Wireless Mesh Networks

Johnathan Ishmael, Sara Bury, Dimitrios P. Pezaros, Nicholas J. P. Race
Computing Department
Lancaster University
Lancaster
LA1 4WA
Email: [ishmael, sara.bury, dp, race]@comp.lancs.ac.uk

***Abstract*—The lack of adequate Internet provision in rural areas is widening the digital divide between town and country. This is proving detrimental to social communication as well as the advancement of rural businesses. Technologies including wireless mesh networking provide an excellent framework on which broadband services can be delivered into deeply rural locations where there is currently little or no infrastructure to offer such a service. This paper details the technical and social experiences encountered during the deployment of a wireless mesh networking infrastructure to the village of Wray, a rural area in the North West of England. We outline the original wireless design, describe the active technical implementation and give a performance analysis of the network in place. We also discuss the social and cultural implications of deploying this technology into the heart of the local community.**

I. Introduction

Wireless Mesh Networks (WMNs) create a resilient infrastructure using a combination of wireless networking technology and ad-hoc routing protocols, together providing the ability to establish networks in places with no prior groundwork. A WMN is a self-managing network in which all nodes act as routers [1] able to route traffic either directly or via a multi-hop path. The system is dynamic in that it is able to adapt to nodes entering and exiting the network, perhaps as a result of a node failure or because of poor connectivity. This robust nature makes mesh networking an ideal technology to use in rural villages where establishing a wired network would be overly complex.

In early 2003 members of a small village community approached the University to find a solution to their lack of broadband Internet access. The community of Wray, situated approximately ten miles form the city of Lancaster in the North West of England, felt strongly that the lack of broadband availability in their village was jeopardising local businesses, education and the community itself. As a result of this a collaboration was initiated between the University and members of the community to deploy WMN technology throughout the village. As well as providing the villagers with broadband access for the first time, the project presented the opportunity for University researchers to investigate the processes and technical challenges associated with the real-world deployment and operation of a mesh network.

The situation at Wray is not uncommon even in today's Internet age; whilst urban areas receive Internet connectivity offering increasing amounts of 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. The research at Wray is looking to investigate alternatives for rural communities still suffering from a lack of suitable broadband services.

This article discusses a range of deployment and operational issues based on three years experience of running the mesh network within Wray. It highlights some of the initial deployment challenges and details a range of technical challenges that had to be overcome in order to ensure the continued success of the service. We conclude the article with a look at the positive impact that Internet access has had on the villagers and a number of local businesses.

II. Related Work

Research within the area of WMNs is active and spread across a number of domains, from Medium Access Control (MAC) layer modifications through to the application layer. Several industrial standards groups are actively working on specifications for mesh networking (such as IEEE 802.11s). There are also a number of organisations operating live WMNs as research testbeds, often though focused on very specific research aims and not concerned with actual provision of service as in the situation at Wray.

One of the earliest established research mesh networks was the Carnegie-Mellon University mobile ad-hoc network testbed [2] which consisted of seven nodes, two stationary and five mobile. Routing was performed using Dynamic Source Routing (DSR) [3] which also integrated the network to the Internet gateway. The research aim was to examine the behavior of the network under varying traffic conditions but the network had no concept of self-management or cognitive configuration. It was deployed within the university itself and only used for purposes of testing, not in a real world environment.

Another university campus-based testbed is the UCSB mesh testbed at UC Santa Barbara [4]. The network is made up of 25 nodes spread across five storeys of a campus building and routing is performed using the Ad-Hoc On-Demand Distance Vector (AODV) protocol [5]. Each node consists of multiple wireless radios, and is made up of two Linksys WRT54G devices, one acting as the AODV router, the second for out-of-band management of the AODV mesh node.

More closely related to the community situation at Wray is the Meraki 'Free The Net' project [6]. It provides mesh connectivity in San Francisco through individuals within the community hosting cheaply obtained custom hardware across the city. The mesh framework was built on ideas stemming from MIT's much earlier Roofnet testbed, as was the Berlin Roofnet project [7] operated by Humboldt University, specifically aimed at improving community aspects of WMNs. Here functionality is provided using a distributed hash table to allow distributed DHCP, DNS and ARP. Every mesh node on the network provides it's own services resulting in seamless roaming between mesh nodes, a more robust failover system and allowing the network to be modified without significantly impacting clients. The testbed itself is implemented within the university by students but the scenario is not accurate for situations such as Wray due to the wide availability of alternative Internet connectivity.

From an industrial perspective, there have been a number of groups investigating mesh networking. Microsoft Research have created a load-able windows driver known as the Mesh Connectivity Layer (MCL) [8] which permits the creation of ad-hoc networks using a modified version of DSR. Nortel have rolled out a series of carrier class WMN products and finally Kiyon [9] has entered the mesh network field creating automation products for small and home offices.

All of the above mentioned WMN testbeds are focused on specific areas of study, none examine the mesh network in a proven real world context. This paper sets out to illustrate how a WMN can function when under real constraints as faced by rural communities.

III. Wray Wireless Mesh Network

The village of Wray covers a geographical area of approximately two square kilometers with the local school situated to the southern side of the village, the public house located to the north west and the majority of homes located on two main streets. An aerial photo of the village taken from the west can be seen in Fig. 1.

The WMN deployed within Wray village consists primarily of LocustWorld Mesh Nodes located strategically throughout the village. The back-bone of the mesh operates using IEEE 802.11b network technology, on top of which AODV provides the routing to the network backhaul, a 5.8GHz wireless link accessed from the local school. Clients connect to the Internet wirelessly via one of the Mesh Boxes, using off-the-shelf IEEE 802.11b network cards.

A. Network Deployment

The school was to provide the initial broadband feed into the village, delivered via a 5.8Ghz radio link (all schools in the region have access to broadband through a government funded initiative). When initially installed, the only choice of inter-network connectivity to the village was satellite, dial-up or the school's radio link connection. It was deemed that the radio connection would be able to carry both interactive and high-bandwidth services. Located on a hill, the school provided an ideal opportunity to allow the signal to propagate across the village to households relatively easily, although there are several blind spots created by hills, tall buildings and large trees. In order to reach these blind spots it is necessary to navigate around them by way of multi-hop links.

Wireless Mesh nodes were sited in strategic locations within the village, determined partly by geography, but also based on areas expected to have high utilisation. Individual Mesh nodes used an externally mounted omni-directional antenna to distribute the signal locally as well as providing connectivity to the village school for the Internet uplink. For redundancy, three Mesh nodes were located at the school (each with a directional antenna).

In the weeks following the initial deployment, we observed unexpected behavior. In particular, connectivity to the Community Hall was unreliable. There were also several blind spots within the village where poor signal levels were experienced, leading to connectivity which

Fig. 1. An aerial photograph of Wray village

was intermittent and subject to high latency. Further investigation revealed that aerials had been positioned too low, or mounted too close to existing television aerials (and experienced signal propagation problems as a result). In general, additional Mesh nodes were installed into locations with poor coverage; the height of existing aerials was also increased to improve the overall network stability and coverage area.

Fig. 2 illustrates the current network topology and coverage area of the Wray Mesh network. The topology continues to be adapted as the requirements and the demands on the network change over time. One of the main factors which affect a change in the network configuration relates to the impact of consumer equipment (such as video senders, etc.) which can interfere with the mesh network. Additionally, the problem of multipath propagation (whereby signals reach the receiver by two or more paths) is particularly evident during the summer months, as radio signals reflect off foliage leading to degraded connectivity for some users.

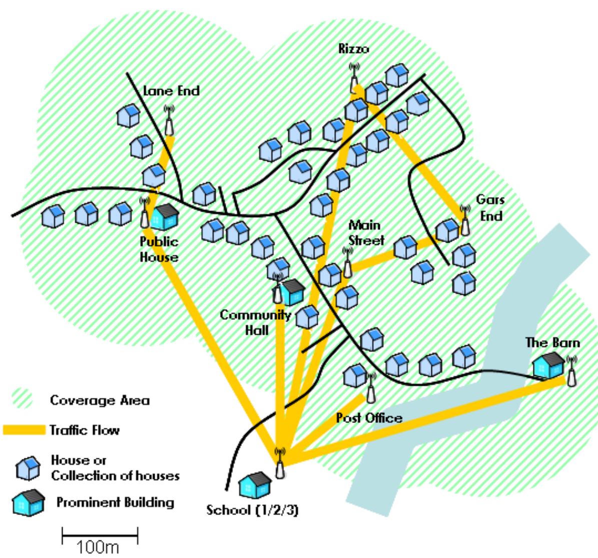

Fig. 2. Final layout and coverage area of the Wray Mesh network

B. Mesh Node Hardware and Administration

LocustWorld Mesh nodes are the predominant hardware platform used within the network [10]. The decision to use off-the-shelf, rather than a bespoke platform was to permit community members to actively participate in the deployment of the network, through purchasing and installing their own devices. It also allows the network to be supported and expanded should the universities' involvement with the project come to an end.

The Locustworld nodes act as both a router (for cross-Mesh traffic) and a point of access (for clients). The device runs a limited version of the Slackware (Linux) operating system which contains the key networking components, user diagnostic tools and a kernel module to provide routing capability. The wireless Ethernet adapter on the Mesh node is a standard 802.11b wireless device with an externally mountable aerial. With the exception of the three aerials at the school, all aerials on the network are omni-directional. Configuration and management is achieved via a series of scripts which modify internal configuration files. The scripts receive a list of configuration options from a portal known as Wiana (Wireless Internet Assigned Numbers Authority) which provides a web-based interface for administering and controlling the Mesh network.

One particular issue identified early within the project was with a minority of users exploiting peer to peer file-sharing services to download large amounts of data. The original configuration of the Mesh allowed a single user to consume all available bandwidth for significant periods of time, thus reducing the performance of the Mesh network for other users. In order to obtain more detailed information about the utilisation of the network we developed our own monitoring system to capture information including details of the individual flows through each node, the amount of latency to gateways and path selection through the Mesh network. This data was then used to analyse overall usage patterns and to highlight heavy and suspect users. The system proved particularly useful in isolating specific problems attributed to individual users or traffic types.

We experienced varying performance from a range of off-the-shelf wireless network adapters which were used to connect households (clients) to the Mesh network. Devices such as USB wireless network cards were typically used by the local community, however their ability to connect to the Mesh network was somewhat mixed. We found that users were overly optimistic – there was a level of expectation that they would be able to connect to the network at all locations internal to a property, without the need for an external antenna. Not surprisingly, in all cases the use of an external omni-directional aerial provided reliable connectivity, although obviously this increased the installation cost significantly. Furthermore, we found that the length of co-axial cable between the external antenna and the indoor wireless network adapter was extremely significant, and we commonly experienced a high degree of loss across this cable. In order to overcome this, a bridging device was used. This connected to the external antenna using a short length of co-axial cable, and then to a user's PC using traditional CAT5 cabling, where loss was not an issue.

The AODV routing algorithm [11] provides decentralised routing, and is typically used on mobile wireless mesh networks. One of the significant reasons for selecting AODV on a static WMN stems from the mesh nodes being located in the user's homes. We considered this to be a hostile environment, with users able to disrupt and unplug nodes at will. As such we considered a reactive protocol to be the preferred choice. Additionally, the use of AODV was consistent with other mesh networks deployed at that time.

During normal operation of the network, it was observed that nodes with relatively poor connectivity were particularly susceptible to noise from other nodes transmitting. Whilst a node would succeed in transferring data over a single hop poor quality link, it would do so only if there no other transmissions in the area. Should a second node (within the range of the poor quality link), begin to transmit, this would result in the original node's link failing, and overall latency across the Mesh increasing.

In order to reduce the use of poor quality links, the minimum signal strength the mesh nodes could utilise was restricted – this effectively forced the mesh to use multiple hops in preference to a single hop. This had the effect of decreasing the latency across the Mesh but also impacted the redundancy available on the network (and the maximum throughput of individual nodes).

C. *Quality of Service*

Providing Quality of Service (QoS) over a wireless medium is particularly challenging [12]. Given that the transmission medium is a licence free band, there are no guarantees that it will be clear when attempting to transmit. This was readily observed when two or more mesh nodes within the same transmission area attempted to simultaneously use the network for large downloads, as latency would increase dramatically.

In order to ensure that no single device (or user) was able to exploit all of the available bandwidth, we placed simple bandwidth restrictions on both the end users and each individual mesh node (this was introduced until such time as QoS mechanisms on wireless networks are readily available). The restrictions use a Leaky Bucket traffic shaping algorithm which is used to control the rate at which data is injected into a network. The algorithm provides a mechanism by which traffic can be shaped to present a steady stream to the network, as opposed to traffic with erratic bursts of low-volume and high-volume flows.

IV. Technical Evaluation

The network has been operational for almost two years and in that time has undergone a number of significant changes. In particular, it was expanded to accommodate increasing numbers of users – the number of Mesh nodes installed within the village has doubled – and configuration changes have been introduced to ensure the fair use of the network between all connected households. The following sections highlight some of the particular issues that have arisen during the course of the deployment and how the community as a whole have evolved as a result of the availability of broadband.

A. Self-* Wireless Mesh Networks

Wireless Mesh Networks (WMN)s have been described by Akyildiz as"dynamically self-organised and self-configured" [1], leading us to believe that network deployment would be trivial. This turned out to be a misconception for the current generation of WMNs, due to factors relating to hardware and software components, and lack of unification amongst them.

Current radio hardware used within WMNs physically restricts the range (power) and conditions (noise/multi-path fading) for device connectivity, resulting in poor or no connectivity when deployment is unplanned. At the same time, poor software decisions can aggravate the wireless radio device behavior even after a planned network deployment. For example, the LocustWorld implementation of a WMN does not balance gateway selection based on parameters such as available bandwidth or connection quality, rather it selects the first available gateway. In addition, gateway selection did not consider AODV's path selection (see section III-B), which in turn did not consider the quality of the radio connections. This lack of the system's component unification led to erratic behavior, contrary to the self-organisation ethos of WMNs. As a result the network had to be manually configured and consequently lost some of its dynamic nature.

B. Network Performance

The bespoke monitoring system developed as an inherent part of the Wray network has been used to evaluate the traffic performance trends and usage patterns experienced by the Mesh's users through its development and continued operation. A large variety of performance data has been collected at a 60-second granularity since November 2005. For each Mesh node, statistics including flow activity, intra-mesh Round-Trip Time (RTT), AODV state parameters, wireless coverage and signal strength are recorded and archived in compressed format. We have indicatively analysed a subset of the collected statistics to show how adequate engineering and network provisioning has resulted in maintaining acceptable service levels.

TABLE I
Load and Utilisation Statistics

Mean Meshbox Load (daily) - KB/s				
	Min.	Median	Mean	Max.
Nov. 2005	2.27	6.2	9.14	25.86
Oct. 2006	2.78	8.28	8.68	17.77
Aggregate Mesh Utilisation (daily) - GB				
Nov. 2005	1.18	3.16	4.75	13.66
Oct. 2006	2.86	7.34	9.0	18.14

Fig. 3 shows two Quantile-Quantile (QQ-)plots comparing the mean mesh node load (in KB/s) and the aggregate network utilisation (in MB) between November 2005 and October 2006, respectively. These metrics have been computed by aggregating all active flows on a daily basis during each month. The 45-degree reference line is plotted to show the distributional similarities between usage patterns of each of the studied periods. The left-most plot shows that the average daily load for each Mesh node does not assume a common distribution between November 2005 and October 2006. Although lower values seem to have slightly increased during the first year of the network deployment, it is evident that for larger values, per-node load has significantly reduced by up-to 32.4%. This is particularly important when examined in comparison to the massive increase in aggregate network utilisation demonstrated by the right-most plot. Daily usage has consistently grown by up-to 55%, reaching 18.14 GB, something graphically evident by the large departure of the quantile points from the reference line. Hence, network provisioning has resulted in a lightly-loaded topology even though daily network utilisation increased in some cases by even a factor of two. Summary statistics for per-node load and aggregate network utilisation are shown in Table I.

TABLE II
Network-wide RTTs (October 2006)

RTTs (monthly) - Milliseconds			
	Min.	Mean	Max.
Min. RTT	10.31	17.88	29.02
Mean RTT	26.66	39.03	58.99
Max. RTT	55.95	74.48	106.30

Fig. 4 is a radar plot of the minimum, mean and maximum RTT experienced by periodic 'ping' polls during October 2006. Each point in the plot shows the

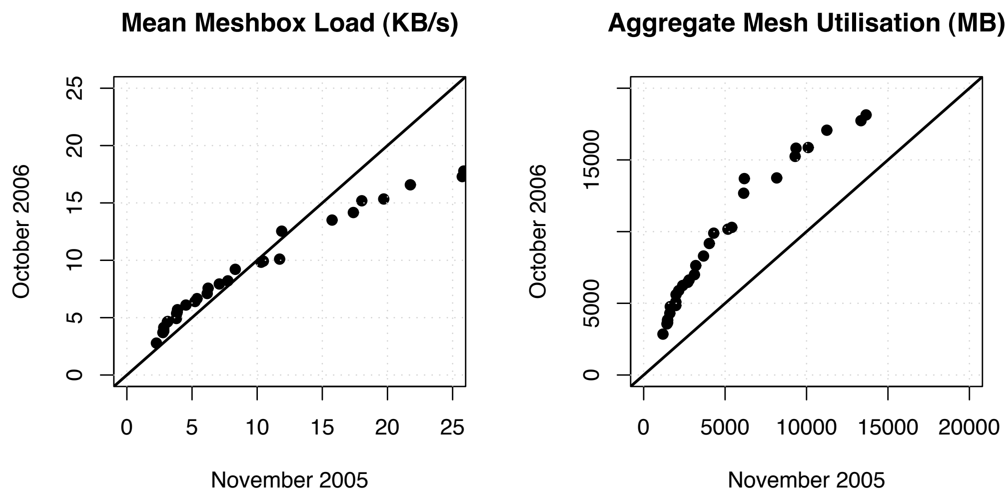

Fig. 3. Differences in mean per-node load and aggregate network usage after a year of network deployment.

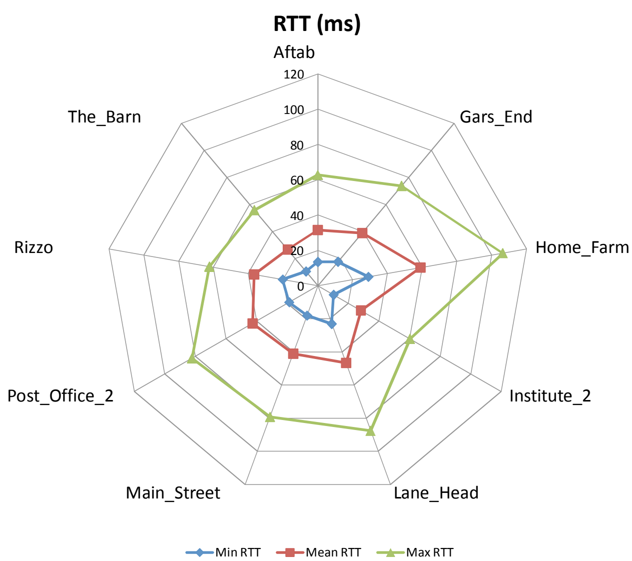

Fig. 4. RTT (ICMP) measurement summary for each mesh node during October 2006.

monthly average of min, mean, and max RTT between each Mesh node and the network gateway, respectively. The radar successfully demonstrates variations in RTT between the different nodes deployed throughout the Wray village. Most importantly, it graphically shows the network-wide overall relationship between the three RTT quantities. The fact that min, mean, and max RTT assume the same relative differences across the Mesh nodes reinforces the argument of adequate network provisioning and light per-node load. Although ICMP-based measurements can be misleading in inferring overall network performance due to the possibility of not being treated identically with the rest of the traffic by the network nodes, large fluctuations in relative differences between RTT quantities would provide an indication of certain paths consistently operating in higher load than others, despite their physical connectivity characteristics. Minimum RTT provides an approximation of the delay attributed only to propagation and transmission times of the medium, whereas mean and maximum RTT also encapsulate the load (queuing) of the network. The radar plot shows that the differences in RTTs between the Mesh nodes are preserved for min, mean and max values. Indeed, these differences in RTTs have been verified to reflect variations in signal strength between the different meshboxes. Table II shows summary statistics of the three RTT quantities.

V. Social Impact

While the focus of our research in deploying a rural community WMN was overcoming the technical challenges faced, the three year deployment also presented significant social benefits.

A. *User Impact*

During the first few months of deployment, network usage patterns had changed from relatively light traffic, to long-lived, high bandwidth flows. When the community was surveyed, it was clear that e-mail communication had quickly been replaced by peer-to-peer applications as the primary network activity. This trend had an increasing negative impact on network performance, which could be coped with by re-educating users, re-designing the network, or imposing strict traffic restrictions ($<$0.5 Mb/s per-user). The latter two options would have resulted in the network not being used to its full potential, hence the only viable solution was to educate the community into changing their usage patterns.

We implemented an acceptable usage policy stipulating that users should not download large files (>100MB) between 9am and 9pm. As users adopted this strategy the peak time latency decreased and speeds increased. The success of this relied on the close nature of the community to spread information in order to improve the overall service.

B. Management Issues

Whilst there any many success stories associated with the introduction of broadband into Wray, a small number of concerns have been raised, relating to the use of peer-to-peer applications, and the increased threat from viruses as a result of insecure (operating) systems. These have necessitated the users' education on end-system security technologies, and on the implications of unauthorised use of copyrighted material. At the same time, the required level of network administration and maintenance is now minimal since the logic behind the Mesh successfully caters for operational anomalies including hardware outages, rerouting traffic as appropriate.

C. Communication and Community Awareness

Technologies such as VoIP, e-mail, instant messaging and blogging are being used to support social communication in the community and to raise the village's profile to the wider region. On-line communication has enabled residents in outlying farms to regularly participate in meetings. At the same time, an increase in physical meetings between the villagers to discuss issues relating to the Mesh network has also been observed. In some cases users within the village are also making use of web cameras in order to keep an eye on elderly relatives.

D. Rural Businesses

Broadband connectivity has enabled Wray's farming community to remain competitive within a highly aggressive market, through the use of IT to register new-born calfs on-line; saving paperwork, postage and most crucially time. The use of e-commerce web-sites has also transformed local stores to international businesses.

VI. CONCLUSIONS

The Wray network has demonstrated how WMN technology can provide an alternative to a wired network infrastructure, offering a community broadband service which exceeds many of those found in urban areas, and providing a real-world mesh networking testbed for the research community. So far, the focus has been to maintain high levels of throughput and low latency to facilitate interactive services such as VoIP. Alongside this we are continuing research into scalable infrastructure provisioning in which components interact to improve the cognitive aspect of the WMNs.

Ultimately the long-term success of any community WMN requires a strong team to sustain and drive forward the network from the heart of the local community. Wray villagers are using their knowledge and experience to help neighboring villages establish their own WMN infrastructures. This initiative is acting as a catalyst for other rural communities in the region, their perception of the success at Wray empowering them to improve their own circumstances.

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