Building Rural Wireless Networks: Lessons Learnt and Future Directions

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ABSTRACT

Providing connectivity to under-serviced rural areas comes with a unique set of challenges such as the high cost of installing equipment, lack of reliable power, skill shortages and high cost of providing Internet connectivity which is mostly satellite based. The recent emergence of low-cost commodity wireless 802.11 devices and the use of mesh networking as a key enabling technology for rural areas could see a new wave of connectivity in these areas. The paper presents pilot deployments of low-cost wireless rural networks in South Africa and Zambia that are showing very encouraging results in which houses, schools and clinics are connected on shoestring budgets. Some key areas for future development are also discussed such the use of IPv6, power saving mechanisms for battery operated routers, and support for real-time flow over mesh networks.

Categories and Subject Descriptors

J.4 [**Computer Applications**]: Social and behavioral sciences

General Terms

Experimentation Human Factors Measurement

1. INTRODUCTION

There are many community-based wireless networks which are emerging in rural developing regions around the globe. Some examples of these networks are: "The Dharamsala Community Wireless Mesh Network [1], mesh networks being set up by CUWin in Ghana [2] and long distance wireless networks being set up in Rwanda, Ghana and Guinea Bissau by the TIER group at University of California, Berkeley [3]. There is also a pattern emerging where wireless mesh networking technology is honed and fine tuned in highly skilled urban areas and later used in rural areas with great success. Examples of this are the Freifunk network in Berlin [4], the MIT roofnet project [5] and the CUWIN network in Urbana [2].

Some of the key issues that make rural wireless networks unique are long distances between nodes, single low-bandwidth gateways to the Internet, high cost of Internet connectivity and lack of reliable power. There are also non-technical challenges when installing technology in developing regions and the TIER group [6] as well as Linknet [7] discuss these. They highlight issues that most researchers would commonly overlook such as transportation issues, tampering and theft, low technical skill level of people in the area, language barriers and cultural barriers.

There are currently two approaches to the construction of community wireless networks. The first consists of a highly planned network with carefully chosen antenna configurations and IP addressing structures to engineer high-quality links with good throughput. This approach is mainly used by community wireless movements in urban areas. It's key disadvantage is that it requires a high degree of skilled users and adding new routers is a complex task. The second approach makes use of a chaotic or sporadic type of network in which community members join the network using a cocktail of various types of hardware but all communicating using an agreed mesh routing protocol which allows them to build routes between each other. This approach allows a network to grow organically and doesn't rely on any centralised administration and is closer to the model that caused the successful growth of the Internet. The business model which could be used to operate a voice and data services in such a sporadic network in a rural village is a village-telco model in which a local entrepreneur manages voice and Internet services as well as inter-connect agreements to connect the village to other operators with global reach.

This paper describes the design of two rural community wireless networks in South Africa and Zambia as well as key social observations that were made and current challenges. The possible future research areas to be addressed such as IPv6, real-time flow over mesh networks and energy-aware routing are then presented.

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2. BACKGROUND

There are many instances where resources are best kept free in order to allow innovation and creativity. For example public streets, parks and beaches and Einstein's theory of relativity are resources which can be freely used without anyone needing to obtain permission to use them. These resources are held in common in the sense than no one exercises any property right with respect to these resources or the exclusive right to choose whether the resource is made available to others [8].

There are some resources which are rivalrous and others which are non-rivalrous, for example if you use Einstein's theory of relativity, there is as much left over afterwards as there was before. But if everyone tries to use the roads or beaches at the same you will get traffic jams and overcrowded beaches and laws are required to control these spaces. The electromagnetic spectrum is another example of a rivalrous resource and has been regulated since 1927.

Most spectrum is only available to commercial operators, however a small amount of spectrum is made available for non-commercial purposes and this is the spectrum which is of most interest to community wireless groups. For example CB and amateur radio uses license-exempt bands to operate and is a self-regulated group which is owned and managed by the users themselves. Community owned wireless networks seeks to put the physical layer in the commons by using licence-free bands such as 2.4 GHz and 5.6 GHz and using spread spectrum technology to allow multiple users to share the same frequency.

Low-cost commodity WiFi based devices. which use these unlicensed bands, can be used to create community wireless networks and create the possibility to cover large areas with free wireless networks. When these devices are combined with Mesh networking, which is able to self-configure and automatically heal itself, it offers a very attractive technical solution for community owned networks.

Mesh networks make use of ad hoc networking routing protocols, some of which are being standardized by the IETF MANET working group [9]. The specific MANET protocol used in the pilots discussed in this paper is the Optimized Link State Routing (OLSR) Protocol [10]. This is a Pro-active or table-driven routing protocol which maintain fresh lists of destinations and their routes by periodically distributing routing tables in the network.

The following section describes two networks which have made use of these low-cost commodity WiFi based devices with some of them running mesh routing protocols. Both of them make use of license-exempt bands and as a result no frequency licensing process was required to be able to install them.

3. REFERENCE NETWORKS

3.1 South Africa: Peebles valley mesh

Peebles Valley and the Masoyi tribal land are located in a hilly area, East of South Africa near the Kruger National Park. The AIDS Care Training and Support (ACTS) clinic, located at the beginning of the Valley, provides medical services to AIDS patients, counselling, testing and Anti-retroviral (ARV) treatment and is the gateway site in the network with VSAT Internet connectivity.

The Masoyi community is under-serviced with most roads remaining unpaved and most houses lacking running water, however electricity is available within the community from the countries only supplier, ESKOM. Power outages are common though, occurring at average intervals of one outage in 7 days, lasting between 3 and 24 hours. The community is poor and has been hugely impacted by AIDS losing many salaried member of households through AIDS which has a significant impact on extended families.

The Peebles valley mesh network, consisting of 9 nodes, is deployed over an area of about 15 square kilometers. It is an International Development Research Centre (IDRC) funded project built to explore a least cost 802.11 network to supply Internet connectivity to the area, being supplied to the ACTS Clinic as well as setup a free local voice service. The clinic connects to surrounding schools, homes, farms and other clinic infrastructure through the mesh network. The VSAT Internet connectivity, which is provided free of charge by a sponsor, is usually underutilized every month, with clinic users only using approximately 60% of the available bandwidth each month.

The satellite link provides 2GB per month at a download rate of 256 kbps and an upload rate of 64 kbps. Once the 2GB capacity limit is reach the Internet connection is cut off until the beginning of the following month and no spare capacity can be carried over to the following month. This spare capacity (which amounts to between 400 MB and 800 MB per month) is shared to users in the mesh network, free of charge but has to be carefully managed by a firewall to ensure that their usage does not effect the clinic's Internet availability. The Internet connectivity costs ($184 per month) are currently being paid for by donor funding.

Figure 1 is a map showing the Peebles valley mesh. Line of sight is not always easy to achieve unless good elevation is available. For example no link is achievable between D and E due to the mountainous terrain. Line of sight is usually possible across the valley and links tend to zig-zag between elevated points on either side of this valley. The dotted lines between the installations show the routes that the OLSR routing protocol has configured. A scale on the map is shown on the bottom left to give an idea of the distances involved. Nodes A,B and C are placed at the ACTs clinic, node D is at an aid organisation called USAID, node E and F are on a nut farm, node G is at a high school, Node H is placed at a nurse's house and Node I is placed at a hospice.

An asterisk server was installed which allowed a VoIP call to be made between the hospice (I) and the clinic (A). Prior to this mobile calls between these two buildings were costing as much as $400 per month. Linux is loaded on all supplied desktop's due to the massive prevalence of viruses and spyware in Windows based systems and due to the large cost saving especially when making use of refurbished PC's. This was also the finding in the TIER projects [6].

See [11] for a detailed analysis of the technical performance of this network

3.1.1 social observations

- Up-time in the network was often severely hampered by users unplugging their equipment.
- It was observed that users who had never been exposed to the Internet, such as the nurse's house or the school, found it difficult to understand how to control their bandwidth usage in spite of usage graphs being available.
- First-time Internet users were easily fooled by Internet scams or Phishing schemes and this highlighted the need to educate users about the dangers of the Internet
- Viruses were very common and these machines often needed to be reformatted. Using Linux based systems minimized the risk of virus attacks as well as reducing the cost of a PC.

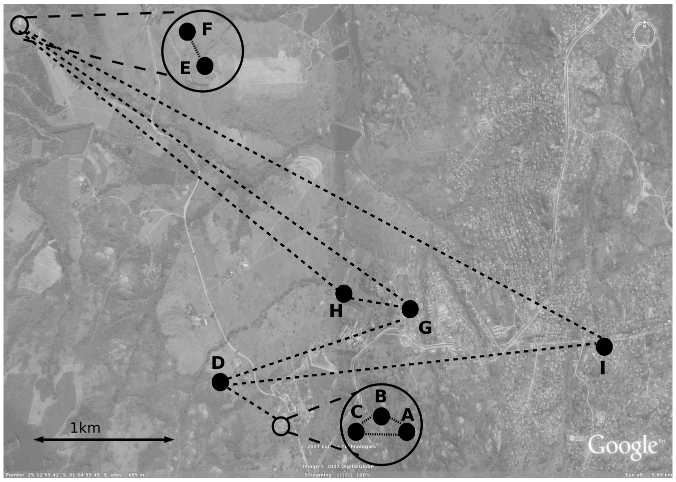

Figure 1: *A map of the Peebles valley mesh. Each solid dot represents a wireless node. An empty dot represents a close cluster of nodes shown in the circles. The area on the left is wealthy farm land and the area on the right is poorer tribal land.*

- Instant messaging tools such as Skype have proved to be a very valuable helpline for inexperienced users in the network. Users would often message more experienced users in the cities to find out how to fix a computer problem or set up a new application.
- Although the VoIP system between the hospice and the clinic was often used for nurses to contact the reception at the clinic, it was not used by doctors as they needed the privacy and convenience of a phone in their practicing rooms and weren't prepared to go to the reception desk.
- The daughter of one of the staff at the clinic who's house was connected to the mesh became the most prolific user of the mesh network. The Internet connectivity was used to look for a job as well as grow her IT skills and as a result of this intervention she now has a good job which makes use of her IT skills.
- GPRS is available in some parts of Peebles valley and wealthier farmers such as the nut farm (node E and F) and USAID (node D) weren't using the network much as the process of reconfiguring their computer to connect to the mesh is seen as a burden.
- It was thought that connecting the school computer lab to the mesh network would stimulate a wave of interest from school pupils, who could use the computers to assist them with school work or improve their computer literacy. However, the person in charge of the lab locked up the lab after school hours and this was not possible as he saw the system as a threat to his own capabilities.

3.1.2 challenges

- This network was built and sustained by skilled IT specialists who were not local to the area, although the final plan was to hand over ownership to a local entrepreneur, this has proved to be very challenging as these sorts of skills are very scarce in rural areas.
- There has been some interest in taking over and expanding the mesh network from a local business specializing in IT services in the area but current legislation around providing access infrastructure in South Africa is not clear and this has made it difficult for individuals to understand whether they can operate a legal business. This particular network was not legal according to the regulation at the time it was constructed but it was built as a proof of concept with the view of challenging the government's policies at the time.
- Making the Internet affordable to the poor rural community in Peebles valley is a difficult task, The typical costs of satellite connectivity is still high at about 11 US cents per MB in South Africa (It can be far higher in other African countries). If the reach of the mesh network is extended to a nearby town 20 km away, it may be possible to link this to a lower cost DSL connection which will bring the cost down to 2 US cents per MB.

3.2 Zambia: Linknet in Macha

Macha is located in the Southern Province of Zambia, 75 km from the nearest town of Choma and 350 km by road from the capital city of Lusaka The topography of the area is somewhat undulating, primarily open Savannah woodland averaging 1,100 meters above sea level. The Macha area is populated by traditional villagers, primarily members of the Batonga tribe, living in small scattered homesteads which usually consist of one extended family. There are no commercial farmers or industries in the area. While much of the population is stable, younger adults move to and from the urban areas of the country. The primary livelihood is subsistence farming with maize being the main crop.

There is an estimated population of 135, 000 (c. 2007) within an approximate 35 km radius around Macha.The average income for a person in the village is $1 per day. Macha has very limited infrastructure. There is a mission hospital, medical research institute and community centre. Only dirt roads link Macha to other villages and towns. Electricity is available to only the privileged few. Moreover, the supply is unreliable especially during the rainy season when several outages can occur within a single day.

LinkNet has provided Internet access in rural Macha since 2004 and no telecommunication operators saw this area as a viable business opportunity. The technical solution implemented in Macha consists of a wireless local area network (WLAN) that is connected via VSAT satellite connections to the Internet. Computers and other user devices connect to the wireless network to obtain access to Internet services. Wired connections are rarely used because they require more installation effort and are sensitive to physical damage as well as lightening.

The challenges experienced in the Linknet project are very similar to those that have been experienced in some of the TIER projects [6]. For example equipment often fails due to voltage spikes and dips and expensive UPS's are required to protect the equipment, transportation is done by air to a local landing strip as road transport tends to destroy hard-drives. Local purchasing is difficult, as much of the specialized wireless equipment is not available and this needs to be purchased in nearby South Africa.

Figure 2 shows LinkNet's current network topology in Macha. The network consist of two VSAT satellite connections, an IT room with a number of servers, switches and routers, and a three layer WLAN (IEEE 802.11g) network to share the Internet connection throughout the community. Each layer uses a unique radio channel to prevent interference with other layers. The top layer of the WLAN network, indicated by dashed lines, is the wireless wide area backbone that interconnects several wireless local area backbones in the middle layer. The local area backbones are formed by mesh clusters (indicated by routers with red labels). The bottom layer is the clientsâĂŹ access layer with hotspots, not shown in the Figure. The mesh cluster is based on the same mesh network that was used for the Peebles mesh network. The skills to build this mesh network were acquired at a training workshop held at the Meraka Institute for Linknet staff as well through a D.I.Y. guide developed by the Meraka Institute [12]

3.2.1 Social observations

LinkNet sees the provisioning of Internet connectivity as a pre-requisite for the development of rural areas. Subsequently, after introduction of the Internet to the Macha community, several unforeseen innovations occurred. These innovations have led to significant socio-economic benefits.

- Sunflower farming: A young man who was born, grew up and educated in the rural Macha community gained access to the Internet through Linknet at the Vision Community Centre in Macha. In mid-2005 he independently searched for new ideas on farming and came across information on sunflower production at two websites. In May 2006 he harvested 70 bags of sunflower seeds, each with a weight of 50 kg from a 20kg bag bag of sunflower seeds he had planted. The oil from these seeds was bartered for maize and used to feed the entire family of parents, four children and five relatives during 2006. During the following season his sunflower production has increased ten-fold.

- Data entry services: A USA-based company needed information from 700,000 documents captured in a database and required some human resources coupled with the availability of the Internet to carry out the task. Macha saw this new business opportunity and created a project branded the âĂIJMacha Conversion ProjectâĂİ which made use of 20 local workers and 2 local project managers working in shifts for 24 hours per day. This project gave School leavers invaluable work experience and brought in much needed revenue to Macha.

- Fight against HIV/AIDS and other infectious diseases: The fight against HIV/AIDS can be vastly augmented with improved quality of HIV care, prevention, and treatment through locally sustained deployment of health communication, clinical, and management information systems. In addition to these primary applications, less extensively trained and less experienced clinical talent has been able to tap into global health expertise via telecommunication services resulting in information-based decisions, thereby improving the quality of care and treatment. A steady supply of HIV/AIDS medicine given is dependent on timely communication and interaction through the ICT infrastructure.

- Local champion: There is a marked difference in the rate of growth of ICT services in an area when there is a local champion. In the case of Macha, a local champion sought to grow their wireless reach and began to explore the possibility of using mesh networking. This led them to set up a training workshop at the Meraka Institute in Pretoria where they learnt how to build mesh networks using the Peebles valley mesh network as a blueprint.

- Distance learning: Many locals that need to study in tertiary applications but don't want to leave their local village are studying through distance learning based Universities such as the Zambian Open University and the University of South Africa.

3.2.2 challenges

- Managing the bandwidth of users is not currently possible and this has led to some abuses by users.

- The environment in Macha is harsh and a large number of computers are damaged or their hard drives fail due to power interruptions, high temperatures and dust.

- Internet connectivity for the entire village is approximately 1.5 Mbps and costs Macha an exorbitant $1700 per month. Locals often visit the Vision Internet Cafe (an Internet Cafe incorporated by LinkNet Zambia) with the desire to use the Internet for the first time but when the charges (per minute) are made known to them, they choose not to use the service simply because they find it unaffordable.

- Email spam being downloaded to the Macha server is very costly as unnecessary Email downloads cost extra money. Linknet has its own email domain and needs a mechanism to filter spam and turn attachments into hyperlinks before being downloaded to a Macha server.

4. FUTURE CHALLENGES AND RESEARCH AREAS

4.1 WISP in a box

There is a need for entrepreneurs in rural areas to have a "ISP in a box" which is essentially a complete gateway unit which allows an entrepreneur to start a business selling Internet and other services into a community wireless network or Internet Cafe. It should have the following core features

1. Make use of best known ingredients from the open source / free software world as well as release all developed code as open source software

2. Easy to use Graphical User Interface

3. Asterisk VoIP server with simple Interface to add new users and Dial plans.

4. User authentication as well as a capture portal with instructions for first-time users

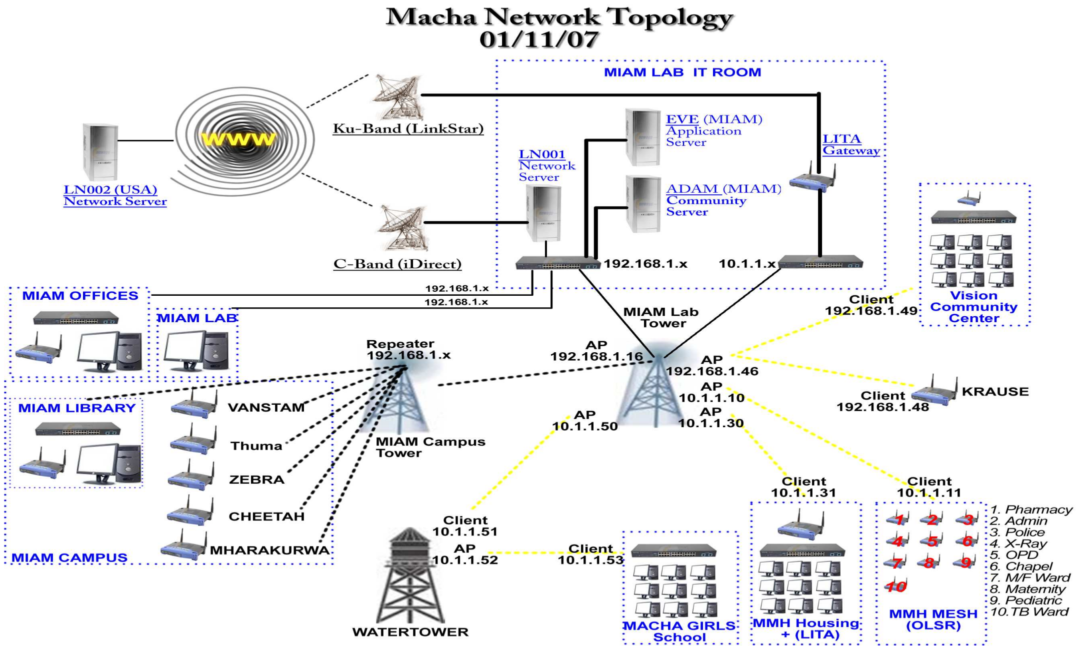

Figure 2: *The Macha network in November 2007.*

5. Provide a billing engine with pre-paid Internet and bandwidth management

6. Provide local content servers such as Wikipedia and distributions of Linux.

7. Transparent proxy server which can redirect commonly requested files such as Windows or Virus updates to a locally available version of the file.

4.2 IPv6

IPv6 has a number of key advantages when used in a mesh network. It offers the ability to auto-configure its IP address based on the MAC address of the Network Interface Card with very little chance of an IP address collision. Many community mesh networks make use of private IPv4 address space due to the lack of availability of IPv4 addresses and then make use of Network Address Translation (NAT) at a gateway. With the large number of available addresses in IPv6, an Internet routeable address can be allocated to every node in your wireless mesh network which makes remote support very simple.

There are still however a number of hurdles to moving over to a pure IPv6 network. All Unix based operating systems offer full support for IPv6 but Windows only offers partial IPv6 support on Windows XP (DNS does not function in IPv6) and full support on Windows Vista. There are also many applications that still need to be ported to IPv6 such as Skype, many SIP clients, email clients and so on. IPv4 to IPv6 tunneling as well as a server which can masquerade IPv6 addresses for IPv4 Internet addresses is needed as a transition strategy for IPv6 users.

4.3 Real-time flow over mesh networks

A key application in rural wireless networks is still voice communication, especially in areas where mobile phone coverage is not available. Video streaming could also become a key application as more advanced applications such as teleconferencing for distance education as well as tele medicine are used. In order to support real time media flow of wireless mesh networks based on commodity 802.11 hardware, new innovative techniques which integrate research progress made in TDMA like protocols as well as adaptive rate coding schemes and real-time sensitive routing protocols are required. A new mechanism which makes use of a multiple-layer framework shown in Figure 3 to measure and characterize the network at various layers as well as provide feedback to individual layers is envisaged. This functionality should also be distributed across the network in order to avoid any central point of failure.

4.4 Energy efficiency in mesh networks

Many rural areas are either without grid-based power or have very unreliable power. If connectivity is to be provided using renewable energy sources or during power outages, there will be some degree of reliance on battery powered wireless routers. There are a number of components required to improve the energy efficiency of mesh networks. Firstly some awareness is needed of the current battery levels of the device as well as the rate at which this device is charging or discharging. An energy aware routing protocol can then adapt the path it takes to ensure that nodes batteries are drained at even rates to ensure the longest possible lifespan of the network (see Figure 3). TDMA like schemes, which make use of time slots, can also be useful to allocate more or less slots to nodes depending on the status of their batteries, this can also be used to allow nodes to enter a sleep state and wake-up when when they have a slot during which they receive or transmit.

5. CONCLUSION

A key factor for the success of any wireless rural network is to have a local champion in the area who will drive the devel-

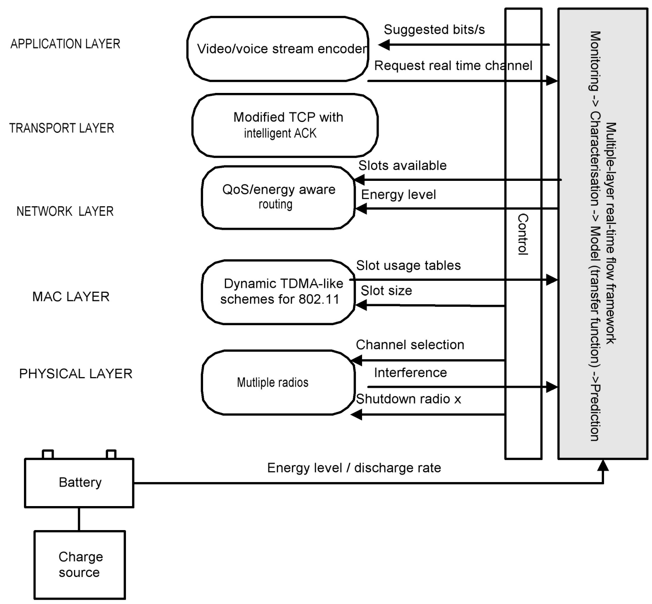

Figure 3: *Real-time flow Framework architecture showing possible messages that can be sent or received from various communication layers*

opment of the network. In the case of the Linknet wireless network in Zambia, all the concepts and ideas came from within the group at Macha and they have achieved rapid success with their network. In the case of the Peebles Valley network, the ideas and the drive came from an externally funded person who didn't live in the area and configured and installed the network with their own skills without a suitable champion to pass these skills onto and take over the wireless network when the project ended. Although a very successful concept has been demonstrated in Peebles Valley, the wireless network is at risk of not being maintained or not growing unless a local champion is found.

The second most important success factor is skills development for locals to carry out support and maintenance of the wireless network. Macha, for example, received skills training workshops from the Meraka Institute to construct mesh networks after seeing what had been achieved in Peebles Valley, ironically they will now grow far beyond the size of the Peebles mesh network with their newly acquired skills.

The rural mesh network in Peebles valley has illustrated that single radio mesh networks based on low-cost commodity wireless equipment is a viable means to provide Internet and local services such as VoIP to an area with limited broadband connectivity.

Due to the lack of skilled users in Peebles Valley, voice and instant messaging applications to link more experienced city users to users in rural areas has proven to be vital helpful when advice is needed on technical issues. Users also need to be educated in rural areas that each of their nodes is often used to repeat the signal in a mesh network and should not be turned off when not in use.

Managing scarce satellite based Internet bandwidth proved to be a key issue in both rural networks. There are a number of other interventions which could greatly assist in minimizing the consumption of the Satellite's bandwidth: 1) Use of a transparent proxy server which filters unnecessary downloads such as windows updates as well as virus updates which can be made available on a local server. 2) Placing local content, such as wikipedia, on a server 3) Making use of spam filters on overseas servers for email.

Wireless mesh networking has enormous potential to redefine connectivity paradigms in the developing world from a centralized operator based approach to a decentralized community-based approach. Wireless pilots such as the ones highlighted have demonstrated the potential of economically empowering disadvantaged communities who are isolated from the global information society. It is hoped these will catalyse further refinement of community based wireless networks to the point where they can rapidly scale to reach the 450 million rural people in Africa and eventually the rest of the developing world.

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