Developing and Deploying Multihop Wireless Networks for Low-Income Communities

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Abstract—**We are architecting and deploying a multi-hop wireless network in one of Houston's most economically disadvantaged neighborhoods. The objective of this network is to empower under-resourced communities with access to technology and educational and work-at-home tools. Here, we present the societal objectives of the network, describe the joint technical and economic objectives that drive its architecture, and discuss future deployment, performance, and research challenges.**

I. Societal Objectives

In many homes across the United States, children, youth, and their families have access to the world's information-technology resources at their fingertips, while in *low-income* communities, access to technology and the opportunities it provides are often limited to brief periods of computer use and Internet access at school or at the public library [1].

Technology for All (TFA)[1] addresses the disparity of opportunity that exists in our cities' low-income neighborhoods through the tools of technology. By working with local community-based organizations, corporations, foundations, technology providers and public entities, TFA creates educational, economic and personal opportunities for low-income persons and the communities in which they live.

TFA and Rice University have partnered to architect and deploy a multi-hop wireless network in some of Houston's most economically disadvantaged neighborhoods, e.g., with per-capita income approximately one-third the national average and 36.7% of children (under the age of 18) living below the poverty line according to the 2000 U. S. Census. Access to technology and Internet resources provides critical educational and job-training resources for a community in which 64.2% of the population of adults over the age of 25 are without a high school diploma or GED equivalent.[2] Indeed, recent research indicates that high school graduation rates improve 6-8% with connected computers at home [2].

[1]http://www.techforall.org
[2]Houston Independent School District, July 2003

Technology For All has numerous programs to utilize the benefits of home Internet access. Through a program called "Learn and Earn," students complete a course and community service to earn a refurbished desktop or laptop. Through the "TFA-JobTech" program with startup funding from the U. S. Department of Commerce Technology Opportunity Program [3], livable-wage jobs are created in the homes of neighborhood residents via document conversion and coding performed via the Internet.[3] TFA-Wireless has also established a relationship with a local community college to provide roof space for antennas on its multi-story building. This relationship will allow the college, which has an extensive online learning and student assistance program, to extend the walls of the classroom to the neighborhoods around the college as the network expands.

The potential benefits to the community are economic, educational and personal. In addition to the potential that TFA-Wireless creates for educational and employment opportunities, some families in the neighborhood are obtaining Internet access in their homes for the first time. Many of these homes do not have land lines. Through TFA-Wireless, they now have connections to resources and applications previously inaccessible, including email communications with family in their home countries.

II. Technical and Economic Objectives

Our design objectives encompass both performance objectives (pervasive Internet access at Megabits per second) and economic objectives (sustainable deployment and operating costs for low-income demographics). Deployment of a new wireline infrastructure is precluded due to costs of deploying new fiber as high as $200,000 per linear mile [4]. Moreover, monthly fees of existing wireline solutions such as DSL and CATV are beyond financial reach within these demographics.

In contrast, wireless technology provides an economically viable solution for low-cost deployment of broadband networks. Yet, even wireless architectures must inevitably connect to the wireline Internet via costly backhaul, averaging $750/month for T1 1.5 Mb/sec access and

[3]http://www.techforall.org/tfa_jobtech.html

$10,500 for T3 45 Mb/sec access.[4] Consequently, we seek to minimize the number of wireline entries from the wireless access network to the backbone Internet.

Under these constraints, we utilize a multi-hop wireless access network architecture as outlined in [5]. In particular, we leverage the economies-of-scale that have driven the costs of IEEE 802.11 components to a price point that is feasible for low-income communities. Moreover, we aggregate all traffic to a single wireline backhaul point and use directional antennas to form long-haul links as needed.

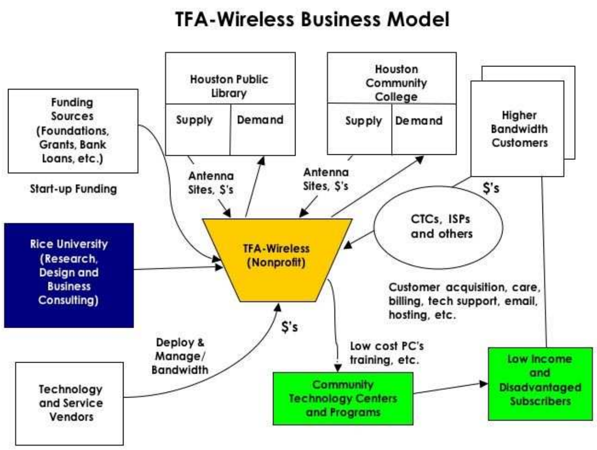

Fig. 1. TFA's self-sustaining business model to offer free wireless Internet to low-income users.

The TFA-Wireless business plan has established a sustainable business model for providing broadband connectivity to residents of the neighborhood (see Figure 1). The model works by charging competitive market rates to customers needing higher bandwidth and commercial service levels while providing free lower bandwidth service (128 kbps) to low-income customers that have Houston Public Library cards. Additionally, all customers with a library card also have access to the SimHouston[5] office productivity software that is available for free download and use by library customers. Both the TFA-Wireless project and the TFA-JobTech project are part of TFA's *social enterprise strategy* to use technology as a tool to empower such low-income communities.

III. Network Architecture

Overview. We have evaluated three commercial off-the-shelf technologies with the objectives of minimizing wireless ISP startup and recurring costs and maximizing the programmability of the platform to foster our research objectives discussed below. Mesh nodes consisting of open-source mesh networking software created by LocustWorld and VIA Mini-ITX hardware with an IEEE 802.11b network card, emerged as the clear choice for our deployment. With one wired entry point, we will use these mesh nodes to provide wireless broadband connections to the businesses and residents of over 4 square kilometers, thereby providing Internet to the neighborhood of Pecan Park.

While the network is capable of access speeds up to 11 Mb/sec, we have chosen more sustainable service levels due to traffic management and tiered pricing objectives. Initially, TFA will provide speeds of 1 Mb/sec and 512 Kb/sec at monthly market rates that are competitive or below that of comparable CATV and DSL connections. An entry level service of 128 Kb/sec will be offered for free to residents.

Hardware Platform. We employ an EPIA VE10000 Mini-ITX Board from VIA Technologies that is a fully featured motherboard measuring 17 cm by 17 cm. The board uses a VIA C3 Nehemiah Processor which is a 1 GHz x86 processor. There are keyboard, mouse, USB, audio, ethernet, PCMCIA, PCI and video ports on the system. We have added an SMC EliteConnect 802.11b 200 mW card into the PCMCIA slot. The PCI slots are used on our dual radio configurations, one for the omni-directional antenna providing access to users and one for the directional antenna for the backhaul connection. The entire system is cased in a NEMA 4 watertight enclosure with the MMCX port of the SMC card running to an N-female connection on the outside of the box for our external antenna. According to FCC regulations, the transmission power of our network card, and the loss through the cables and connectors, we have chosen a 15 dBi omni-directional antenna to connect to each mesh node. These antennas are mounted atop 10 meter masts. The systems run a Linux kernel with LocustWorld mesh software which use AODV routing [6] to wirelessly multihop back to the wired gateway.

Performance Targets. For our primary performance constraint, we are targeting a connection of 1 Mb/sec for commercial connections. The speed of the wired backbone to the Internet is scalable but initially capped to 3 Mb/sec. The mesh nodes have an efficiency loss with each additional hop from the wire for independently active traffic flows. Moreover, they have a bandwidth bias for flows that are fewer hops from the wired node when multiple flows are active. Thus, we can feasibly perform a maximum of four hops from the gateway mesh nodes at TFA and to meet the 1 Mb/sec target at the most remote hop.

Network Topology. We found that using only omni-directional antennas within the network was not sufficient to cover the entire neighborhood according to the above

[4] http://www.pathfinderbandwidth.com, May 2005
[5] http://www.simdesk.com

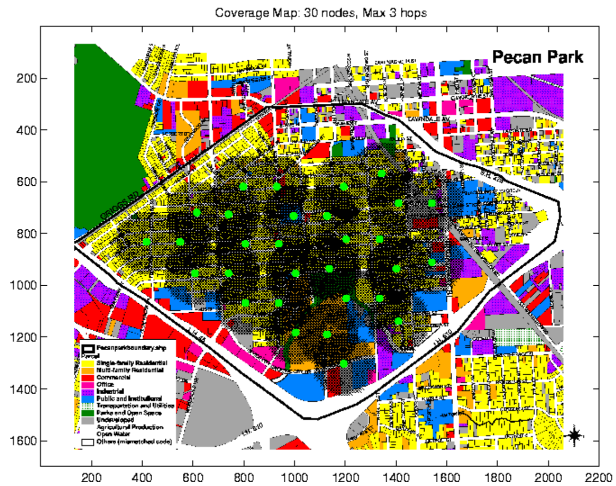

Fig. 2. Network architecture for Pecan Park (over 4 square kilometers) using LocustWorld mesh nodes with hexagonal packing and a maximum of four hops from the wired node.

performance constraints. Using a 15 dBi omni-directional antenna, the mesh node has a range of 225-275 meters in every direction depending on the density of tree coverage within the immediate area of the neighborhood of that antenna. However, Pecan Park is greater than 2 kilometers long, and TFA is on the far east side of the neighborhood. The four hop limitation using omni-directional antennas restricts us from reaching the far west side of the neighborhood, the locale most populated by potential commercial customers. Thus, we use 24 dBi directional antennas at both TFA and the Melcher Branch Library in the center of Pecan Park. Additionally, this one kilometer directional connection approximately doubles the coverage area of the network. All other mesh nodes within within the network use only omni-directional antennas. We use a hexagonal packing scheme to minimize the cost of the network for the desired coverage area with distances between mesh nodes set at 250 meters and a maximum of four hops from the wired node (see Figure 2).

IV. Future Work

Extensibility. We are currently in the deployment stage of the project. As described previously, all but two antennas within the network are omni-directional. In the future, other low-income neighborhoods in Southeast Houston will be covered using additional directional hops to spatially reuse the wireless signal and additional wireline entry points as needed. With the four hop limitation, it is possible to have two additional directional hops from both the TFA building and Melcher Library (see Figure 3). The proposed network would span fifteen square kilometers, reaching the homes of over 40,000 residents. With the increased number of users, it will be necessary to upgrade to IEEE 802.11g technology to have up to 54 Mb/sec in wireless backhaul. The increase in bandwidth at the backhaul would ease the four hop limitation and allow the network to grow even further.

Research Challenges. While it is impossible to program the physical layer and MAC layer protocols because of the non-programmable nature of the PCMCIA cards, the open-source programmable Linux kernel within each mesh node allow layer 2 rate control, TCP design, and routing protocol changes. Our focus will be on congestion control and TCP design specifically for multihop wireless networks. A key advantage in each of these areas is that we are able to use real as opposed to simulated network traffic as data for experiments.

In contrast, the Transit Access Points (TAPs) project at Rice is a completely clean slate design of custom multihop wireless hardware with 400 Mb/sec Multi-Input Multi-Output (MIMO) antennas and novel MAC protocols that, among other things, opportunistically send high rates according to the quality of the channel and ensure TAP-aggregate fairness per node [5]. Nonetheless, the research objectives of the two platforms provide synergy to study the above research issues in environments ranging from programmable off-the-shelf hardware to fully custom FPGA designs.

Measurement Study. A vital step in the development of our research platform will be automating a means to perform experiments and record measurements. We will employ SNMP and tcpdump in our network to monitor traffic statistics of users within the network. Also, we will emulate important multihop scenarios using traffic gener-

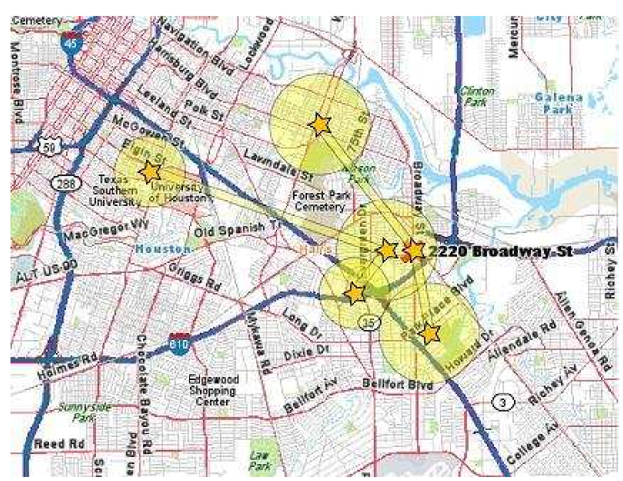

Fig. 3. Potential future expansion to 15 square kilometers of wireless coverage for Houston's East End neighborhoods.

ation scripts. One such experiment will flood packets to the wired node from each of the different hops away from the wire. Traffic statistics will be collected to measure the TAP-aggregate fairness characteristics of our protocol. Thus, critical research objectives can be explored due to the programmability of the platform while simultaneously providing a valuable technological resource to low-income communities.

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