Cell-Share: Opportunistic Use of Cellular Uplink to Augment Rural WiFi Mesh Networks

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***Abstract*—The Internet has revolutionized communication, education, commerce and information access for its users worldwide. Unfortunately, the lack of copper/fiber infrastructure in the rural areas of the developing world has prevented a large majority of the human population from reaping the benefits of the Internet. While the number of mobile subscribers in the developing world has more than quadrupled in the last five years, the adoption of the Internet has shown a slow growth pattern. Recently, there has been a growing interest in providing Internet access to rural areas by means of inexpensive long distance WiFi mesh networks. However, the expensive Internet uplink and the difficulty in troubleshooting of WiFi mesh networks has hindered their large scale deployment. In this paper, we propose *Cell-Share* – an architecture that leverages the explosive growth in cellular network penetration in the developing world to provide rural WiFi mesh networks with an on-demand scalable Internet uplink and troubleshooting back-channel using a collaborative mobile phone framework. We implement *Cell-Share* on Windows Mobile and Android platforms to demonstrate the feasibility of using the infrastructure of cellular data networks to provide a back-channel for network troubleshooting as well as capacity enhancement for rural mesh networks.**

I. Introduction

The information and communication infrastructure of any region plays a pivotal role in its socio-economic development and can be regarded as one of its greatest assets. With rapid advances in the field of communication technology and information access over the past few decades, the world has entered the *communications age*. The growth of the Internet has played an integral role in this information revolution. Unfortunately, this revolution contributed in the development of only a small portion of the human population, confined to the contemporary developed economies of the world and the urban areas of the developing nations, resulting in a "digital divide". A vast majority of the people living in the rural areas of developing and under-developed nations have yet to take advantage of the Internet revolution. Figure 1 highlights the disparity in the availability of electricity, fixed-telephone service and some form of public Internet facility in the village communities of the world, as estimated by the International Telecommunication Union (ITU) – a United Nations agency for Information and Communication Technology (ICT) issues [11].

† **Statistics source for Figures 1, 2(a), 2(b):** ITU/BDT research available at http://www.itu.int/ITU-D/ict/statistics/ict/index.html

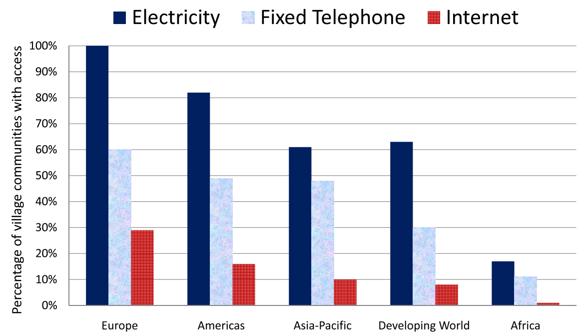

Fig. 1. Availability of Information and Communication Technologies in villages around the world. (Statistics 2001-2006)†.

One of the main reasons behind this technological divide has been the fact that for a long time networking research has focused primarily on improving connectivity in the developed world, while rural regions in developing and under-developed countries continued to lack in even basic connectivity solutions. According to the *ICT* statistics released by the ITU†, by early 2008 there were only 1.5 billion Internet users in the world and about half of the world's population did not own a mobile phone. A closer look at these statistics reveals that there are major regional differences and the real distribution is quite skewed, with the ICT penetration levels in the developed economies being an order of magnitude greater than developing nations (refer to Figure 2(a)). For example, the number of Internet users in Asia is less than 20% of the total population and a mere 5% in Africa, while the rest of the world has on an average more than 40% of its population online. The disparity is worse for broadband users as many African nations do not have broadband access. These statistics bear testimony to the fact that of the 6.7 billion people inhabiting this planet, the majority still remains completely untouched by the benefits of the digital revolution. While there has been an impressive growth in the number of mobile phone users in the last decade (refer Figure 2(b)), Internet use is not growing as quickly in the developing world.

Over the past few years, there has been a growing interest in providing low-cost connectivity to rural areas using WiFi [2], [6]–[8], [17], [22]. Based on this research, deployments of research and community networks have begun to connect remote areas to nearby cities. For example, a network set up by the TIER group at UC Berkeley [22] in Southern India has been used to provide dedicated voice and video conferencing

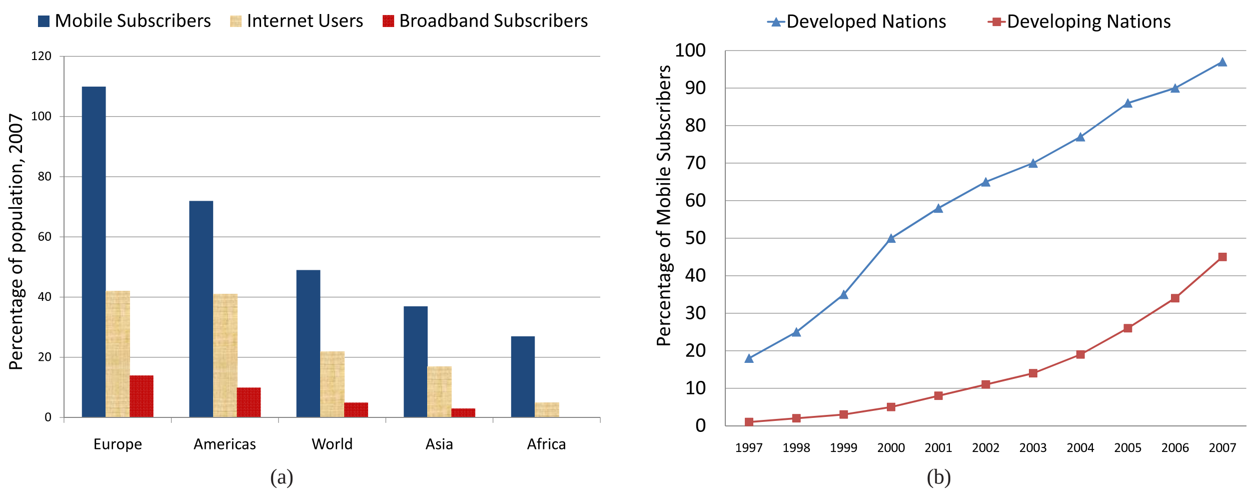

Fig. 2. Distribution of ICT services at the end of 2007 (a) and the growth in the number of mobile phone subscribers between 1997-2007 (b)†.

facilities between clinics located in remote villages and the Aravind Eye hospital for tele-medicine. The Wireless Africa project has a deployment in Mpumalanga [12], that is aimed at sharing the satellite Internet connection of an AIDS clinic with the neighboring schools, hospitals and homes using a WiFi mesh and providing local VoIP telephony. The mesh network in Dharamsala, India [7] provides not only Internet access to people in the hilly town, but also local voice calling and video streaming services.

While these projects have made significant strides towards providing basic connectivity to rural areas in developing regions, there are a number of challenges that have prevented their large scale adoption. To begin, the lack of efficient remote network monitoring and debugging solutions, erratic power supply, and voltage fluctuations in rural areas often lead to node failures and network partitioning [19], [21]. Further, environmental factors and mechanical failures result in disconnected nodes that are difficult to troubleshoot, for example, antenna misalignments. The lack of a reliable back-channel renders the disconnected portion of the network unusable, even if local WiFi is still available, as the link to the far-away gateway node is severed [16], [19], [21].

Due to the high cost of an Internet uplink in rural areas, many of these initiatives focus on providing a single point of connectivity (community Internet and phone kiosks) in a village [3], [5], [16], [20]. Such a network architecture, that is designed to extend connectivity from an Internet gateway to a single point in a village, over carefully planned long distance WiFi links [14], [15], becomes vulnerable to a single point of failure or bottleneck. In a network where a few gateway nodes serve a large number of communities, the Internet gateway capacity often becomes the bottleneck. Further, in the absence of a back-channel, a link failure can result in the disruption of connectivity for a large number of users.

In this paper, we propose Cell-Share – an architecture that leverages the growing trend in mobile phone coverage throughout the world (refer to Figure 2(b)) to augment rural WiFi mesh networks. We develop a system that allows the use of Internet enabled mobile phones as a back-channel to provide temporary Internet connectivity to disconnected portions of the network; a feature that can greatly facilitate remote troubleshooting of network partitions. A key advantage of the Cell-Share architecture is that by opportunistically aggregating the cellular data uplink of multiple mobile phones (owned by local mesh users), additional uplink capacity can be provided to nodes that are located far-away from the gateway and obtain proportionally lower throughput than nodes near the gateway.

In the rest of the paper, we discuss the architectural choices for wireless connectivity in rural WiFi mesh network deployments. In Section III we present the design of the Cell-Share system that has the potential to opportunistically use cellular infrastructure to help enable wireless mesh networks in providing affordable and viable communication services to a large number of users in rural areas.

II. Rural WiFi Mesh Networks

The network structure of a rural mesh network can be broken down into three components: the backhaul that connects the mesh to the Internet (if present), the local mesh through which network-side devices communicate, and the mesh router to client link. One or more mesh routers may be connected to the Internet and act as gateways. Within the mesh network, routers form a relatively static topology and, optimally, are equipped with multiple radios. Each mesh router also acts as an access point providing WiFi connectivity to end devices. On the backhaul, a number of technology choices are available, such as satellite, point-to-point long-distance WiFi links, WiMAX, or a wired DSL connection. Figure 3 shows the network architecture of a typical of a rural WiFi mesh network, that extends the reach of a single satellite Internet connection to a large community [2], [6]–[8], [17], [23].

A. Backhaul Uplink Wireless Technologies

The lack of copper and fiber communication infrastructure in developing nations necessitates the use of wireless access technology, which has the scope for maximum impact in these regions with minimum investment. In recent years, the exponential growth of wireless technology has made laying

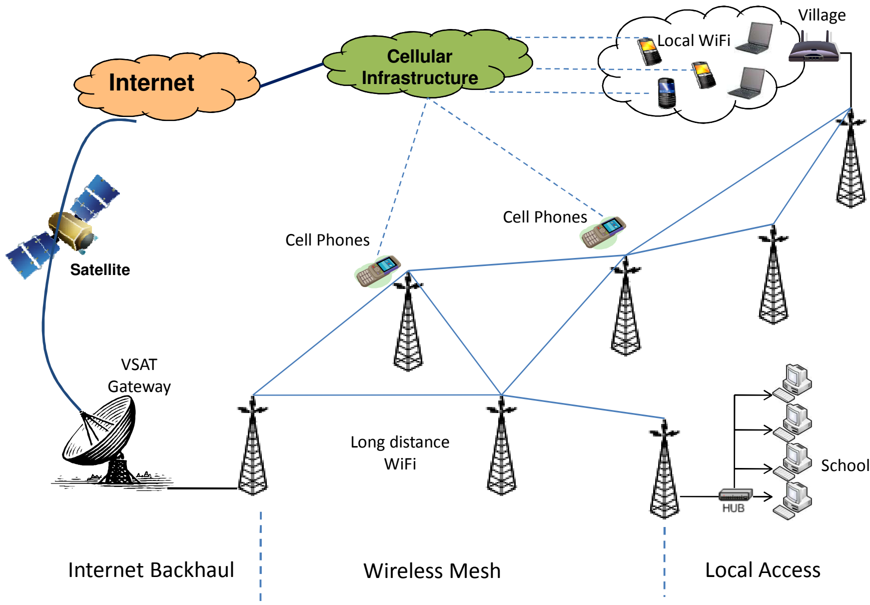

Fig. 3. Rural mesh network architecture.

of copper lines to an analog phone far more expensive than providing wireless broadband connectivity to the Internet. Fortunately, a variety of wireless Internet connectivity options exist.

Satellite networks provide high bandwidth and are useful for remote areas where there is no existing infrastructure. However, the cost of a VSAT link is often prohibitively high for low income rural regions. For example, in Somaliland, Africa, the installation cost of a typical VSAT link that can operate at speeds of up to 2 Mbps is estimated to be approximately US$35,000, with a recurring cost that depends on the link capacity, but which can be as great as US$2000 per month for a 128 Kbps downlink and 64 Kbps uplink connection [9]. At such a high installation and recurring cost, only large enterprises can afford VSAT, typically making it unsuitable for small community deployments.

WiMAX operates in a licensed frequency band and has a centralized network architecture with a range of up to 50 km. The IEEE 802.16j amendment defines a mobile multihop relay extension that allows WiMAX base stations that do not have a backhaul connection to communicate with base stations that do have such a connection, in a tree topology [10]. Due to its licensed operation and high infrastructure cost, WiMAX technology is most suited to the needs of broadband connectivity in urban areas, where the cost of the expensive infrastructure is amortized by a large number of users - an assumption that does not hold true for low income rural areas. Lastly, WiMAX technology has yet to be adopted on a large scale in not just developing but developed nations as well.

Cellular network penetration is growing at a rapid pace in developing nations. Figure 2(b) shows that in just a five year period from 2002 to 2007, the number of mobile subscribers in the developing world has more than quadrupled. One of the main reasons for the emergence of cellular phones as a key communication technology worldwide is the incremental nature in which cellular networks have evolved. The network providers usually upgrade their networks from one generation of technology to another (GPRS, EDGE, 3G, 3.5G, 4G), rolling out the latest technology in the urban areas first, which then gradually trickles down to rural areas with time. Most cellular networks in both Asia and Africa now support data communication. An amalgamation of cellular data networks with rural WiFi networks is a promising and viable evolutionary approach to provide Internet access to the developing regions of the world.

In the future, the recently unlicensed white-space spectrum in the US and parts of Europe has the potential to serve as an inexpensive means to connect remote areas. However, since the availability of the white-space spectrum became possible due to the transition from analog to digital TV transmission, such a spectrum may not become available for unlicensed use in the developing nations in the near future.

III. Cell-Share

We now present the design of Cell-Share – a system to form transient local Internet gateways using one or more mobile phones with a data connection. The motivation for the design of Cell-Share comes from the rapidly growing reach of cellular networks in the developing world. In areas where the cost of subscribing to a dedicated satellite connection or the absence of inexpensive DSL or WiMAX uplinks makes it difficult for small scale community mesh networks to survive, the ability to establish an aggregated Internet uplink using multiple cell phones on-demand can prove to be a significant boost for rural mesh networks. Cell-Share enables the network users to opportunistically enhance their uplink capacity by allowing the mesh network to use the cellular data connection (such as GPRS/EDGE/3G) of Internet enabled mobile phones. The cellular uplink can also serve as a back-channel to help the network administrator debug and troubleshoot network failures from a remote location.

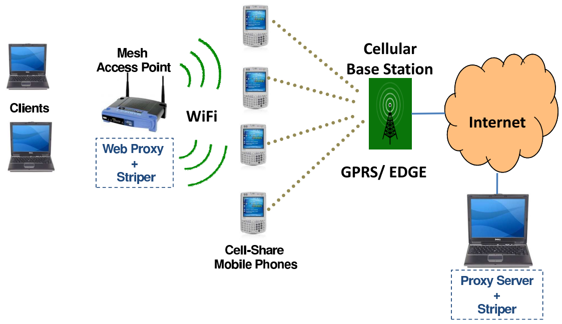

Fig. 4. Cell-Share architecture.

A. System Design

In the Cell-Share architecture, one or more users can volunteer to have their cell-phone uplink be used to support the local mesh. As shown in Figure 4, multiple Internet enabled cell phones can associate with a mesh access point like any other WiFi client. After association, the user can start the cell-share application, which informs the mesh router that the cell-phone is capable and willing to offer its cellular uplink for use by the mesh network. Following the initial handshake, the mesh access point starts using the connected mobile-phone as a gateway device. Traditionally, when a WiFi client connects to an access point, it uses the Internet uplink of the access point to route data to the Internet. In the Cell-Share architecture, we use a client-gateway architecture where a mesh access point may use its WiFi clients (in this case the Cell-Share mobile phones) to reach the Internet. This is achieved by forming a TCP (for reliable delivery) tunnel between the mesh access point and a remote proxy server on the Internet, via each Cell-Share mobile phone as described in Section III-B.

The client nodes in the network are configured to use a local proxy server running on the mesh access point, a feature already used in most rural mesh networks for caching and content filtering. The mesh access point communicates with a remote proxy server on the Internet via multiple Cell-Share mobile phone tunnels. All traffic between the local proxy on the mesh router and the remote proxy server on the Internet is striped on each of the available tunnels for capacity aggregation. The web proxy running on the mesh-access point delegates its client web requests to the Internet proxy server, which acts on its behalf and fetches the content from the Internet like a conventional web proxy. The responses are transported back to the proxy on the mesh access point over the tunnels using striping. In other words, the mesh access point transfers its state to the Internet proxy server in a transparent fashion.

B. Testbed Implementation

We have implemented a proof-of-concept Cell-Share prototype on Android and Windows Mobile platform based phones. To ensure ease of implementation and portability of the Cell-Share architecture across different mobile phone platforms, we keep the functionality on the mobile phone to a minimum. The mobile phones run an application that acts as a simple byte-exchanger between two TCP connections: one connecting the mesh router to the mobile phone over the WiFi link and the other between the mobile phone and the remote proxy server over the cellular uplink. We implement the local and remote proxy servers in the Ruby programming language. The transfer of proxy requests and responses occurs over the TCP tunnels via the Cell-Share mobile phones.

As shown in Figure 4, our testbed is comprised of four Windows Mobile smartphones that have a GPRS/EDGE cellular uplink, running the Cell-Share application. We use two IBM laptops. One acts as a proxy server connected to the Internet using a DSL connection. The other laptop acts as a mesh access point that forwards the traffic from its connected clients to the Internet proxy server via the four Windows mobile phones running Cell-share over the TCP tunnels. For simplicity, in our current implementation, the mesh access point only routes the data of its connected clients through the Cell-Share system, but not the traffic from other mesh nodes.

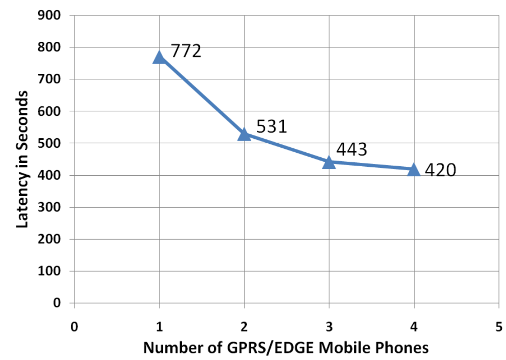

Fig. 5. Striping across multiple gateway phones.

To verify that the cellular uplink of multiple Cell-Share mobile phones can be aggregated effectively to provide a reliable and scalable back-channel, we run a typical web browsing traffic load comprised of HTTP requests to several news, search and other popular websites. Figure 5 shows a plot of the time taken to finish a given browsing workload with a varying number of Cell-Share phones contributing their bandwidth. The download time is reduced on increasing the number of collaborating mobile phones, indicating that the Cell-Share setup and striping mechanism is able to effectively aggregate the uplink of the available mobile phones.

C. Future Directions

In a scenario where a network can have a varying number of transient gateway nodes, several interesting research questions arise. Traditionally, a rural mesh network relies on a fixed capacity uplink for Internet connectivity. Since there are only a small number of gateways in a mesh network, the problem of routing is limited to the identification of the shortest path to the nearest gateway. However, in an architecture where multiple cell-phones act as temporary gateways, albeit with smaller uplink capacities, the problem of routing can no longer remain agnostic of the difference in the uplink capacity of a gateway. Thus, such a system would require changes to the routing protocol to account for multiple variable capacity gateway nodes that remain active for a short period of time.

IV. Related Work

In [19], the authors identify the existence of a reliable back-channel as a key requirement for the troubleshooting and sustainability of rural mesh networks. The authors report that even in remote villages in India, they observed that more than one cellular network provider was present, allowing them to use SMS to send power and antenna readings to a remote monitoring server. While this served as an important first step, it did not provide the authors with a two-way communication channel. In [21], the authors use the GPRS data connection of a mobile phone to establish reverse SSH tunnels over a HTTP proxy for remote monitoring and debugging. However, both these approaches require a dedicated mobile phone to be present at each mesh node in the same enclosure and connected via a serial/USB port. Since the mesh node and the mobile phone share the same power supply, the mobile phone back-channel often shares the same fate as the mesh node in the event of a power failure.

In contrast, Cell-Share allows the opportunistic use of multiple cell-phones as a back-haul over a standard WiFi connection, obviating the need for a dedicated mobile phone and enabling support for on-demand use of a mobile phone connection. In addition, we provide a mechanism to aggregate the capacity of multiple cell-phones for use as an additional uplink, thereby removing the constraint on the bottleneck capacity of a single data connection. There have been a number of proposals in the past for bandwidth aggregation of multiple devices [1], [4], [13], [18]. While these solutions focus on improving the performance of a single client by using the wireless links of multiple devices, the focus of our work is to augment the capacity of wireless mesh networks in a dynamic and scalable way for use as a mesh gateway. Such bandwidth aggregation solutions are complementary to our work and can be used in conjunction with Cell-Share.

V. Conclusion

A vast majority of people living in the developing world, especially in the rural areas, have yet to experience the benefits of the Internet, the adoption of which has been hampered by the lack of proper communication infrastructure. On the other hand, there has been an explosive growth in the number of mobile subscribers worldwide. In the last couple of years, several projects to offer Internet connectivity in rural areas have been initiated by research groups and communities in different parts of the world using inexpensive WiFi devices. However, these projects face several challenges such as difficulty in troubleshooting distant nodes in the event of a network partition. In this paper, we have proposed Cell-Share – a framework to create on-demand back-channels for troubleshooting rural WiFi mesh networks, as well as to provide additional Internet uplink capacity, by enabling multiple mobile phones to aggregate their cellular data uplink capacity. We believe that an amalgamation of cellular data networks with rural WiFi mesh networks is a promising and viable evolutionary approach to providing Internet access to the developing regions of the world.

VI. Acknowledgements

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