PhoneHome: Robust Extension of Cellular Coverage

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***Abstract*—Ubiquitous cellular coverage is often taken for granted, yet numerous people live outside, or at the fringes, of commercial cellular coverage. Further, natural disasters and human rights violations cause the displacement of millions of people annually worldwide, with many of these people relocating to shelters and camps in areas at or just beyond the margins of existing cellular infrastructure. In this work we design PhoneHome, a system prototype that extends existing cellular coverage to areas with no or damaged cellular infrastructure, or infrastructure that is otherwise poorly performing. We explore the feasibility of PhoneHome and address current limitations and future directions for independently operated, user-extensible cellular infrastructure.**

***Index Terms*—Mobile telephony, Local cellular networks, Access divides, Displacement, Low-cost communication, Bottom-up infrastructure**

I. INTRODUCTION

Connectivity has rapidly become an essential need. In fact, connectivity is so critical that the United Nations has gone so far as identifying Internet access as a human right [1]. Unfortunately, high-quality connectivity is far from universal, particularly in disadvantaged rural areas or in locations where displaced populations settle (e.g. refugee camps, post-disaster shelters). There remains a significant number of people living in poorly-connected areas around the world. Cellular networks are often touted as the most plausible solution for providing connectivity in such regions due to their relatively cheaper investment cost than that of traditional wired infrastructure. Unfortunately, despite the lower investment cost, mobile infrastructure is often not economically viable for commercial providers due to low subscriber density and lack of purchasing power.

One of the most pressing needs for displaced people in times of crisis is cellular voice and data connectivity. Not only do they need to remain in contact with family they have left behind, they need to reconnect with missing kin who may have been lost during relocation. There are a number of recent cellular-based programs that help displaced persons in this regard. For instance, a program offered by MTN and Ericsson provided free cell phones to Sudanese living in select refugee camps in Uganda [2]. For these programs to be successful, displaced people must have cellular access. Complicating matters, settlements of displaced people are often established in rural, undeveloped areas, leading to a dearth of connectivity options.

One promising solution for providing connectivity to residents of poorly-connected areas is local, community-scale cellular networks. Recent advances in local cellular networks have lowered the entry-point for constructing small-scale wireless networks [3], [4], [5]. Because of the reduced coverage footprint and energy requirements, the cost of such networks is a fraction of that required to build traditional cellular infrastructure, making it economically feasible to provide coverage in areas where the expense of traditional infrastructure had previously made installations impossible to justify.

We leverage local cellular network technology to create *PhoneHome*, a system prototype designed to extend cellular coverage from a commercial carrier into an area where the carrier does not offer sufficient, quality coverage, or where coverage does not exist. PhoneHome introduces three critical functions: (i) it independently provides cellular coverage into poorly-connected areas; (ii) it localizes the cellular core, enabling local cellular traffic regardless of the presence or absence of global connectivity; and (iii) it virtually extends nearby commercial coverage without requiring commercial carrier involvement.

In this work, we design PhoneHome to operate within the limitations imposed by currently available technologies. We also illuminate the constraints as an entry point into our exploration of future systems solutions for community-owned, 'bottom-up' extension of cellular coverage. PhoneHome demonstrates an alternative, carrier agnostic, avenue for providing high-quality connectivity in areas where existing infrastructure is unable to meet the user demand.

II. PHONEHOME APPLICATIONS

Commercial cellular coverage is dictated by simple economics; carriers deploy infrastructure in areas where the user population is large enough to justify the high capital expenditure. This reality leads to a relative lack of quality coverage in rural, poor areas where the potential subscriber base is sparse. People living in such areas experience diminished ability to obtain connectivity during high user demand [6], if connectivity is available at all. PhoneHome is designed to extend existing cellular coverage into areas with poor quality or non-existent connectivity. In this section, we provide example case study locations where we have witnessed poorly performing cellular infrastructure and believe that extension and localization of existing cellular coverage would provide a benefit.

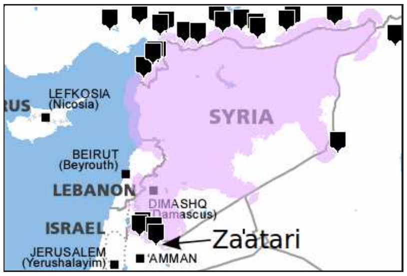

Fig. 1: MTN Syria coverage map with camp locations. [7]

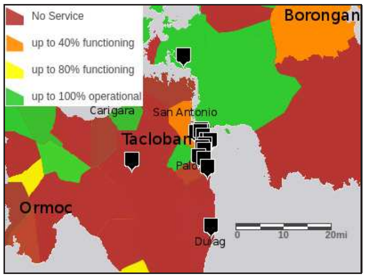

Fig. 2: Cellular coverage map two weeks after Typhoon Haiyan [8].

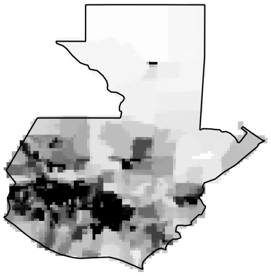

Fig. 3: Guatemala population density. Dark areas indicate higher density.

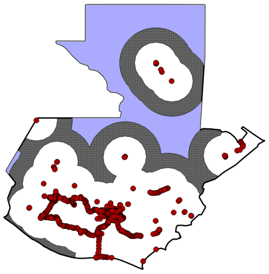

Fig. 4: Movistar coverage in Guatemala.

A. *Communication from refugee camps*

As an initial case study, we examine the plight of Syrian refugees. Recent conflicts in Syria have led to over 4 million [9] Syrian refugees as of August 25, 2015 and construction of refugee camps in multiple neighboring countries near the Syrian border (see Figure 1). The Za'atari refugee camp, located in Jordan 10km from the Syrian border, has rapidly become one of the largest refugee camps in the world, with a population reaching over 200,000 at one point since its inception in June 2012. As a result, infrastructure and services have struggled to keep up with the exploding population. The cellular infrastructure of the three Jordanian providers that serve the camp area was installed before the camp was constructed, making it woefully under-provisioned with regard to the number of residents who now need to use the networks. We visited Za'atari for three days in January 2015 and collected cellular broadcast messages to characterize the camp-serving infrastructure. We found evidence of extreme cellular congestion on multiple carriers, frequently resulting in the inability for residents to gain service [6]. Interestingly, residents have discovered a small hill within the camp where they are sometimes able to connect directly to their Syrian provider [10], allowing them to use Syrian SIM cards and avoid international calling rates to contacts back in their home country.

Refugees who are displaced from their home countries due to civil unrest often resettle immediately across the border of their home country. Figure 1 illustrates the locations of some of the refugee camps near Syria [11]. In the figure we see that cellular coverage easily "leaks" across political boundaries into neighboring countries. Refugees will often pursue these connections, even at their own peril by traveling back into war torn areas, to circumvent international calling rates to communicate with family back home [10], [12]. PhoneHome is ideal in such a scenario, extending coverage of the nearby carrier so as to avoid the need for users to place themselves in danger.

B. *Connectivity post-disaster*

In scenarios of relocation due to natural disaster, low quality cellular access is also likely, as shelters form in rural areas outside, but nearby, damaged cities. An example is shown in Figure 2, which maps cellular coverage and shelter locations two weeks after Typhoon Haiyan passed over the Philippines in November of 2013. As the figure shows, most of the sites are in areas with degraded service; however, most shelters are *near* areas with better coverage.

C. *Rural connectivity in 'fringe' areas*

To illustrate the pressing need for connectivity in 'fringe' areas, we investigate geographic coverage in Guatemala. We leverage population density information from [13] as well as the OpenCellID database [14] to map base station coordinates for the three major cellular carriers, Tigo, Claro, and Movistar. The population density is a 1-km grid shaded based on the number of inhabitants per square, as shown in Figure 3. Due to fundamental timing constraints, the maximum distance a GSM mobile device can be from a base station is 35km. We therefore buffer each base station by 35km to generate the map shown in Figure 4. Note that the coverage areas (white) depicted do not reflect real-world conditions and in fact represent best-case, maximum coverage for all base stations. Coverage is, in reality, diminished by terrain impacting line-of-site and user demand. To conserve space, we only include a coverage map for Movistar. As expected, all three carriers focus coverage on highly populated areas.

We can estimate the number of people living outside, but *near* cellular coverage. We buffer all base stations by an additional 25km and calculate the population of people living in the area between 35km and 60km from the base stations (grey shaded areas in Figure 4). We find that Tigo has a total of 17,438 people living in these 'fringe' areas, Claro has 35,294, and Movistar has 113,795. These areas represent opportunities for extending existing coverage using a system such as PhoneHome.

III. CHALLENGES

There are a number of challenges to provisioning affordable cellular service in areas with poor coverage. In this section, we describe these challenges, and outline technical mechanisms for addressing them.

***Challenge**: lack of cellular signal*

The most fundamental challenge facing cellular connectivity in marginal areas is the absence of commercial coverage.

Typically, economic incentives do not exist for companies to deploy infrastructure in fringe areas. In the past, the cost and complexity of cellular network infrastructure meant it was infeasible to own and operate a network on a small-scale. However, this paradigm is shifting due to recent work leveraging low-cost, low-power software defined radios as well as open source software such as OpenBTS[1]. Costing less than $10k, community-scale cellular networks have been successfully deployed in sites around the world where carrier coverage was lacking [3], [4], [15]. These systems hold much promise for providing connectivity where commercial coverage does not exist or is not sufficient.

***Challenge**: poor performance of existing networks*

In many cases users in fringe areas are actually within the coverage of existing wireless carriers. However, infrastructure that exists in such areas is typically not provisioned for the sudden increase in demand created by displacement, or is not adequately provisioned for existing populations. As such, performance of cellular networks in locations such as refugee camps, post-disaster shelters, or rural areas is often quite poor [10], [16]. In these cases there is a need to augment the existing coverage or to reduce the burden on the commercial networks.

***Challenge**: global connection requirement*

Femtocells provide functionality somewhat similar in spirit to PhoneHome; however, they require an Internet connection to function, as they create a tunnel into a wireless provider's core using packet-switched networks. While local cellular networks can provide autonomous local services, they also require a connection to the Internet in order to provide global cellular services. Unfortunately, reliance on Internet availability poses challenges to the use of both technologies in limited connectivity environments; in many cases the only option may be costly satellite connectivity. Hence, there is a need for a solution that does not require a traditional Internet backhaul link.

***Challenge**: interference with existing networks*

A fundamental requirement for user-operated cellular networks is that they must not interfere or degrade service for existing wireless infrastructure (i.e. any system must not occupy radio spectrum used by any nearby carrier). Traditionally, wireless carriers license spectrum from governmental regulators where the license defines the allowed frequencies and the specific locations for their infrastructure. This approach, while appropriate for regions with high spectrum occupancy, is more rigid than necessary in areas at the margins of existing coverage. Affordable software-defined radios (SDRs) have lowered the entry point for reliable spectrum sensing and characterization [16]. SDRs can continuously sweep the cellular frequency bands in search of incumbent wireless signals in order to build an occupancy map.

***Challenge**: reachability*

PhoneHome shifts users onto an independent cellular network that, given current limitations, makes the users unreachable from commercial carriers. This creates a rendezvous problem where we must make PhoneHome users globally reachable. PhoneHome needs to serve three types of caller-callee requests depending on the user network associations. These requests are (i) Local-to-Local call, (ii) Local-to-Commercial call (i.e. outbound) and (iii) Commercial-to-Local call (i.e. inbound). Each of these scenarios requires the system to make a decision to route calls depending on the destination number. The first scenario is straight-forward: if both the caller and callee are on the local network, the call will be bridged locally [4]. The second and the third cases pose increasingly challenging problems. The outbound case requires bridging of calls to the appropriate destination commercial network. As detailed in Section IV-B, this problem is solved by the PhoneHome anchor modems. Last but not least, the challenge with inbound calls is how to make local users visible to the outside world, so that the commercial network knows that a user can be found in the local network. This challenge is also solved by the anchor modems.

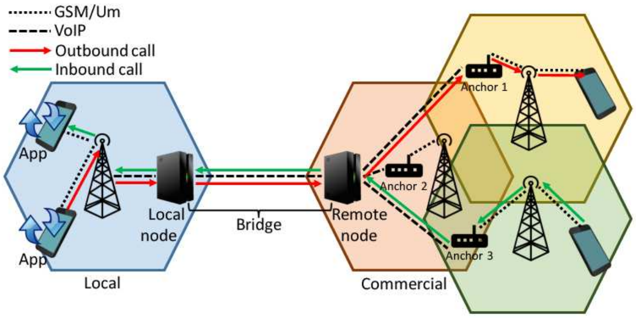

Fig. 5: PhoneHome system diagram. Users connect their mobile devices to the local cellular network. PhoneHome uses a long-distance wireless link to a remote relay node in order to bridge local cellular services onto commercial carriers near the remote node.

IV. SYSTEM DESIGN

PhoneHome, as illustrated in Figure 5, consists of (i) a *local network* that operates in the outskirts of cellular coverage; (ii) a *PhoneHome bridge* comprised of two physical nodes – a local and remote; and (iii) the *PhoneHome smartphone application*. The local network provides cellular connectivity to clients using their unmodified cellphones and SIM cards. Using the PhoneHome bridge, the local network also provides a virtual extension of the commercial network's services to the outskirts. The bridge consists of two physical nodes that are connected via a long distance wireless link. The local node is situated in the desired coverage area (outskirts), while the remote node is positioned within the commercial provider's coverage area. The link between the local and remote nodes serves as a bridge between the commercial carrier and the outskirts. Beyond physical connectivity, the PhoneHome bridge provides translation of GSM signals to VoIP and back to GSM in order to bridge local and commercial traffic while using

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[1] http://www.openbts.org

low-cost IP backhaul. Finally, the PhoneHome application automatically switches users between the local and commercial networks based on their usage.

The remainder of this section details our system prototype implementation. We start with an overview of local cellular networks in Section IV-A. We then delve in the design and implementation of the PhoneHome bridge in Section IV-B. Finally, we describe the PhoneHome application in Section IV-C.

A. Local cellular networks

Local cellular networks have been proposed in recent years to address the communication needs in disconnected or fringe areas [4], [3], [16]. These networks make use of free open source software, open hardware and generic IP backhaul in order to bring down the cost of cellular network deployments several orders of magnitude [4]. Since local cells are backward-compatible with commercial cellular standards, users can harness their existing phones and SIM cards to gain connectivity.

A typical local cellular network consists of a base station that runs open source implementation of the GSM stack such as OpenBTS. This base station communicates via the GSM protocol with user devices through a Um interface. Once GSM signals are at the base station, they are converted to a Voice over IP (VoIP) session and handed to the local network's core for authentication and switching. This transition from GSM to VoIP allows the use of inexpensive IP backhaul. The local network's core also makes use of open source software for traffic switching and authentication. While there are several options for such implementation, in our work we use a combination of FreeSwitch[2], Sipauthserve and, Smqueue[3]. For more detailed description of local cellular networks' integration and operation we refer the interested reader to our previous work [4].

B. PhoneHome bridge

One of the key contributions of this work is the PhoneHome bridge. The main purpose of this bridge is to provide virtual extension of the commercial coverage to the local network. There are several challenges associated with this virtual extension concerned with (i) the bridge integration, and the routing of (ii) outbound and (iii) inbound calls. We detail these in turn.

Bridge integration. The PhoneHome bridge is comprised of a local node and a remote node. As illustrated in Figure 5, the local node is connected to the local cellular network on one end and to the remote node via a long-distance wireless link on the other. The remote node, in turn, makes use of a set of anchor modems to interface with the commercial network(s) and bridge calls globally. Both the local and remote nodes run FreeSwitch and handle the voice/text traffic as VoIP. For this purpose, the nodes are configured to bridge VoIP sessions from the local network to the bridge (at the local node) and from the bridge through the anchors to the commercial network (at the remote node).

Fig. 6: PhoneHome remote node equipment. The remote node includes a PC, GSM devices to bridge traffic onto a nearby commercial carrier, and a long-distance Wi-Fi antenna to connect to the local node within the camp.

In terms of implementation, the local node is typically integrated with the local cell's core and is implemented on top of the local network's FreeSwitch instance. The local network is, in turn, equipped with a long-distance antenna to establish the wireless link for the PhoneHome bridge. The remote node is a Linux PC running FreeSwitch and equipped with several anchor modems and a long-range wireless antenna. The anchor modems can be implemented using any device that features cellular baseband, such as cellular USB dongles, GSM modems, or Android cellular phones. Figure 6 illustrates our remote node prototype that is comprised of a Linux PC running Ubuntu 14.04 and FreeSwitch. Our prototype makes use of Android phones as anchors running the built-in SIP client to interface with FreeSwitch in order to bridge calls between the local IP backhaul and the commercial GSM/Um interface.

As mentioned in Section III one of the critical challenges for PhoneHome is to handle rendezvous for outbound and inbound calls. **Outbound calls** are established from a local user to a commercial user. After bridging the call to the remote node, our current prototype triggers the appropriate anchor to initiate a call via GSM/Um to the destination commercial node and then bridges this call with the corresponding VoIP session in order to connect the local and the commercial users. The key point to note here is that the anchor establishes the final stretch of call to the commercial user. This approach results in a major drawback: that is, the callee sees a call from an unknown number and may choose to ignore this call or wrongly search for the local user using the anchor's number.

Our future work will resolve this problem through the employment of electronically programmable SIMs (eSIMs) at the anchors. A key advantage of eSIMs is that their identity can be reprogrammed on the fly, which will allow the anchors to impersonate the local user before bridging the call to the commercial user. The latter will completely resolve our previously outlined drawback of the current approach as callees will see calls from a known number.

Inbound calls, on the other hand, are initiated by a commercial user and are destined for a local network user. In order to establish such calls, the commercial network needs to know that a particular user is reachable in the local network. This is unfortunately impossible, since commercial networks are

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[2] https://freeswitch.org/

[3] https://github.com/RangeNetworks/smqueue

unaware of local networks. This requires the local network to be proactive in receiving incoming calls. To this end we employ added functionality to the anchors, that enables them to continuously monitor *pages* on the commercial network. Pages are broadcast messages that inform mobile devices of incoming calls or SMS, triggering the target device to request a private communication channel. PhoneHome inspects pages and determines whether the desired mobile device is in fact connected to the local network.

In our current implementation, the PhoneHome application will trigger a PHY-switch causing the local user to disconnect from the local cell and connect on the commercial in order to receive the call. There are two major problems with this solution. First, in cases where the commercial network is congested or failing, inbound calls will fail. Second, as detailed in Section V-C, the PHY-switch may take up to 40 seconds, depending on carrier and technology. Taking into account that pages typically timeout within 10 seconds and carriers can configure whether or not they are repeated, it is possible that despite a successful PHY-switch, the call will still fail due to page timeout.

These problems will be resolved in the next version of our anchors, which will use eSIMs. The anchors will continuously monitor the broadcast channel of their respective commercial network for pages whose destination is in the local cell. Whenever such page is intercepted, the anchor will perform e-switch, which will change the identity of the anchor to that of the paged local user. The anchor will then be able to accept the incoming call on behalf of the local user and bridge that call to the local user. We anticipate electronically reprogramming SIMs will result in shorter switch times compared to PHY-switching.

C. *PhoneHome application*

The final component of PhoneHome is our smartphone application that performs two key tasks. First, it provisions users in the local network by reading and submitting their IMSI to the local network via SMS. Users with the PhoneHome application can use any GSM SIM card with PhoneHome, including valid or expired SIMs from any provider. This functionality practically allows system operation without the need of customer service and support. While traditionally phones will only connect to the cellular base stations associated with their SIM card provider, our application uses an internal Android API to switch between available cellular networks at will, without user interaction, regardless of the issuer of the user's SIM. The second task the application performs is intelligently switching between the local and commercial networks based on user behaviors. As discussed in Section IV-B, user phones must shift between networks to receive inbound calls from the global network. Our application automates network switching without requiring the user to manually change settings.

D. *Illustrative examples*

To illustrate the operation of PhoneHome, let us consider two example scenarios of operation: one with an outbound and one with an inbound call. These two scenarios are illustrated in Figure 5, where the red path presents an outbound call, while the green path presents an inbound call.

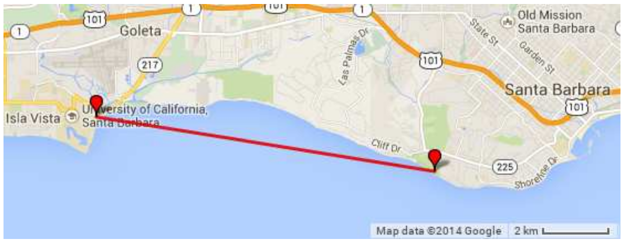


Fig. 7: Long-distance Wi-Fi link locations used for experiments.

First, in an **outbound scenario** (designated in green in Figure 5), the local user dials a destination number. The call request travels from the phone to the local base station via the GSM/Um interface. Once at the base station, OpenBTS translates the GSM/Um signal to a VoIP session and forwards the call to FreeSwitch over the IP backhaul. FreeSwitch, in turn, checks the destination number and determines that this call is to be connected globally via the bridge. At the local node, FreeSwitch then bridges the call to FreeSwitch at the remote node via the long-distance wireless link. The remote node bridges the VoIP session to the corresponding anchor. Once at the anchor node, the call is once again translated from VoIP to GSM/Um in order to enter the commercial network and be connected to the global user. We note that with our future eSIM-based design the line of action will be the same, except that the anchor will impersonate the callee before completing the call.

For PhoneHome to receive an **inbound call** (designated in red on Figure 5), the orange anchor continuously monitors pages on the shared control channel to determine whether a local user is being called. When the anchor receives a page, it notifies the local network that a user is being called. The local network, in turn, triggers a PHY-switch by querying the PhoneHome app on the respective phone. If commercial coverage is currently available, the local user will migrate on the commercial network and will complete the call. We note that this chain of events will be very different in our future eSIM implementation of the anchors. With an eSIM, as soon as the orange anchor receives a page, it impersonates the local user who is being called and receives the call on this user's behalf. The anchor then bridges the call through a VoIP session with the local cell. Ultimately, the local cell completes the call by establishing a GSM session between OpenBTS and the local user.

V. EVALUATION

We evaluate PhoneHome in a local testbed to appraise its efficacy in extending cellular coverage. For the purposes of our experiments, the local cellular network consists of a single Range Networks [17] Snap Unit GSM base station, which utilizes a Range Networks RAD-1 GSM transceiver, a 1W

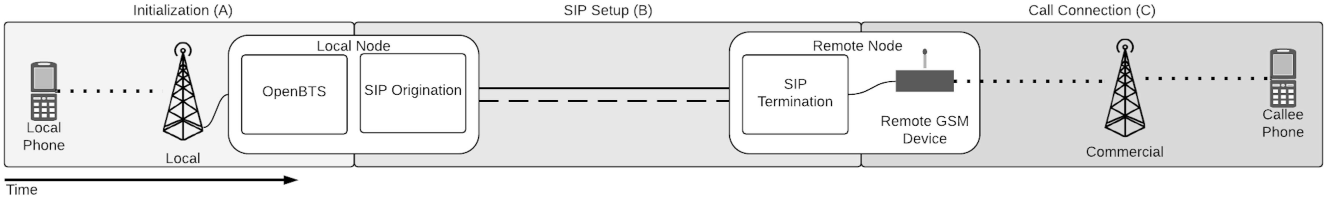


Fig. 8: Call setup latency components.

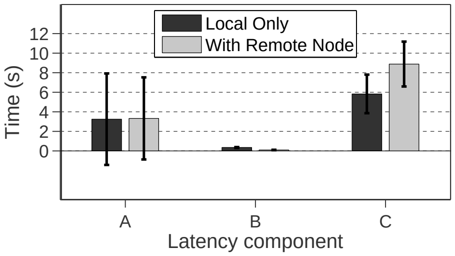


Fig. 9: Latency comparison for call setup.

amplifier, and the OpenBTS 4.0 software stack. The local side of the bridge uses a Ubiquiti Rocket M5 with a sector antenna to operate a point to multipoint 5GHz Wi-Fi network, enabling one or more remote nodes to connect.

To evaluate the network performance with the presence of a remote node, we build a long-distance testbed link. We connect a remote relay node to the local node in our testbed using a roughly 10km 5GHz Wi-Fi link. The link locations are shown in Figure 7. Our remote node consists of a Lenovo X61 laptop running FreeSwitch, two Galaxy Nexus Android devices, and a Ubiquiti AirGrid 23dBi antenna. The remote node computer connects to commercial carriers using the two Android phones as anchors, one with a T-Mobile SIM and one with an AT&T SIM. Each phone is connected to the remote node via USB to provide power and signaling, and via 3.5mm cables to bridge call audio between the remote node and the phone.

A. Call setup latency

We examine latencies introduced by each of the call setup components in PhoneHome with and without the presence of a remote node. We define ***initialization*** as the time between a phone on the local cell dialing a number and the local base station establishing a session. ***SIP setup*** is the time taken by FreeSwitch, the IP-based private branch exchange (PBX), to set up a call. The final measured component is ***call connection***, the time between call initialization on the local or remote node and the callee's phone ringing. The three components with a remote node present are illustrated in Figure 8.

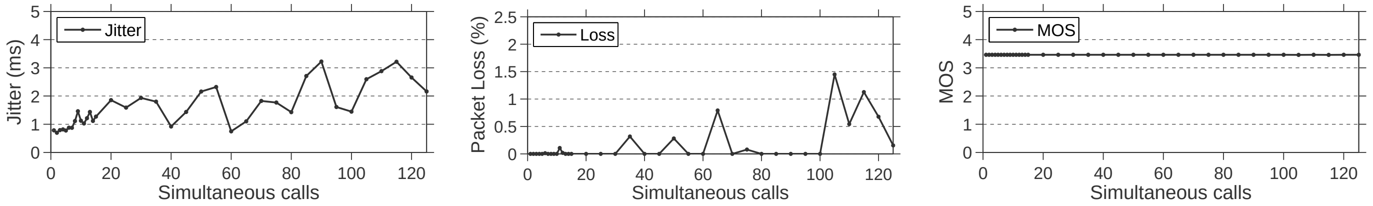
We evaluate the latency for each component by placing 30 consecutive calls from a phone on the local network to a commercial carrier using a remote node, then placing 30 calls from one phone on the local network to another local phone. The results are displayed in Figure 9. The bar values correspond to the mean time and the error bars indicate standard deviation. We observe that initialization (A) and SIP setup (B) components are similar in both scenarios. Call connection (C) is the only stage where we see significant latency added when a remote node is present; roughly three seconds is added to the total call setup time. We believe this 30.66% additional latency is within tolerable limits for users. It is important to note that the latencies we measure in this section correspond to call setup only, not in-call latency. In-call latency is explored in the quality of service (QoS) section.

B. QoS

We investigate voice session quality with the presence of a long-distance wireless link. We increase the number of voice sessions running across the 10km wireless link from 1 to 125 simultaneous calls with 700Kbps of background traffic. We choose 700Kbps as the maximum GPRS bandwidth per OpenBTS instance is 140Kbps with the highest coding scheme and the maximum time slots dedicated to data traffic. Given this maximum, we inject traffic representing five local nodes using the remote node.

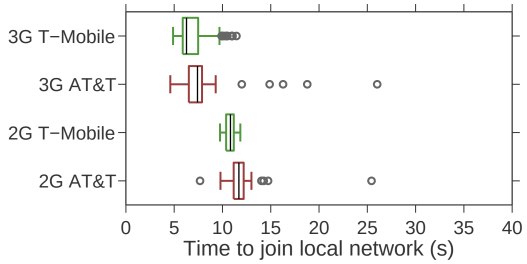
Latency, jitter, and packet loss are crucial metrics to determine voice quality. We first measure latency across the 10km wireless link. The ITU G.114 recommendation [18] specifies an upper threshold for one-way latency of 150 ms as satisfactory performance. The mean one-way latency for our 10km link is 28.09 ms and the median is 27.54 ms, well within the tolerable limit. We next investigate jitter and find that as simultaneous call load increases, the mean jitter value only slightly increases, as shown in Figure 10a. The measured values are clearly within acceptable limits. Packet loss is displayed in Figure 10b. As with jitter, we see a slight decrease in performance as the number of simultaneous calls surpasses 100. However, the overall loss observed remains acceptable.

Mean Opinion Score (MOS) is a metric used to describe perceived call quality, with a score between 1 and 5 where 5 is excellent and 1 is very poor. The maximum achievable MOS is dependent on the codec used to digitize the audio. In our case, the codec used is GSM-FR (6.10), which corresponds with a maximum MOS of 3.46. We calculate the expected MOS using the E-model [19], which is dependent on both packet loss and the audio codec. Figure 10c shows that the calculated MOS values are stable and near the maximum achievable score

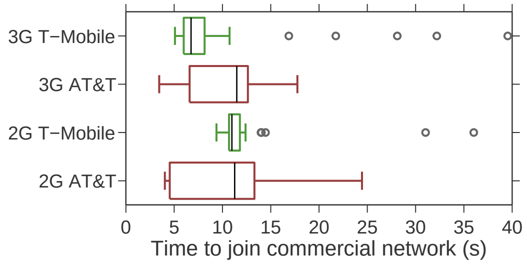


(a) Jitter. (b) Packet loss. (c) Mean opinion score.

Fig. 10: Long-distance link QoS measurements.



(a) Commercial to local camp times.



(b) Local to commercial camp times.

Fig. 11: Camp time comparison.

for all evaluated loads. Overall, we see that the transmission of voice traffic across our 10km link does not unacceptably degrade the QoS of calls.

C. *Camp times*

We explore *camp time*, the time taken by a phone to switch to a different network. Camp time performance is an important factor in the current version of our system as the PhoneHome smartphone application causes the phone to change networks in order to receive incoming calls from the commercial carrier. During the transition between networks the phone is offline; hence the amount of time spent camping on networks determines whether or not the incoming call will be missed due to page timeout. We utilize two Samsung Galaxy Nexus phones for this experiment, switching between a commercial cellular network and a local cellular network roughly once each minute for one hour for a total of 120 measurements. To understand how the technology used by commercial carriers impacts camp time, we repeat this experiment twice, with the phones configured to prefer 2G or 3G commercial networks.

Figure 11a shows camp times for phones transitioning from AT&T and T-Mobile networks (both 2G and 3G on each) to the local cell. We observe distinct performance differences between 2G and 3G devices, with 3G camp time values of roughly half of 2G camp times. In the worst case, AT&T 2G, the camp time for the local cell is 25 seconds. We also explore camp times for phones transitioning in the other direction, from the local network to the AT&T and T-Mobile networks. Figure 11b depicts our results. We see more variable performance compared to the ingress camp times with AT&T 3G no longer consistently outperforming 2G. We posit that this may be due to stronger signal strength for the 2G network. Overall, we see camp times of less than 15 seconds for both ingress and egress cases. We believe that such performance makes PhoneHome feasible, as pages typically use 10 second timeouts and most carriers configure unanswered pages to be repeated at least once.

VI. RELATED WORK

Local cellular networks: Our work leans heavily on recent work in delivering cellular service on a small scale. OpenBTS [20] is an open-source GSM base station that has been used in many research projects [3], [21], [4] to provide community-scale cellular coverage in rural and underdeveloped areas. In contrast to these prior works, our focus is not on providing small-scale access to a specialized carrier, but virtually extending the coverage of commercial wireless carriers to previously uncovered areas. We leverage the prior findings to aid us in making informed decisions in our system design.

Coverage extension: Ubiquitous cellular coverage has long proven to be a challenge in resource-poor areas, with researchers exploring coverage in difficult environments through the use of technologies such as cellular repeaters [22]. However, a major limitation of repeaters is that amplifying and retransmitting raw signal means that users must still be within the 35 km maximum distance between a mobile device and a base station for GSM. PhoneHome also localizes cellular traffic whenever possible and the local network can operate during commercial network failure. Another popular response to lack of coverage has been the use of femtocells [23], in which a low-power cellular base station device tunnels to a carrier's calling infrastructure via a broadband Internet connection. While similar in spirit to these techniques, our system does not require an Internet connection.

Cellular coexistence: Community-owned cellular networks must coexist peacefully with nearby commercial cellular networks. Nomadic GSM addresses non-interfering frequency selection for base stations [5]. This work relies on user handsets to scan the GSM frequency range, requiring active local cell users to discover incumbents. Our previous work, HybridCell [16], monitors commercial carrier control channels to determine frequencies used by incumbent carriers without relying on local user handsets. PhoneHome incorporates techniques used in HybridCell to operate in a non-interfering manner.

VII. DISCUSSION AND CONCLUSION

We envision PhoneHome as a starting point for exploring user-extensible, bottom-up communications infrastructure in locations where connectivity is unlikely to be improved by commercial carriers. Many open questions remain for the idea of third-party network extension, pointing to important directions for future research. For instance, how many GSM devices are required at the remote gateway in order to provide adequate scaling given some number of users on the local network? How can we leverage electronically reprogrammable SIMs to provide global connectivity without forcing the user phones to switch to commercial carriers? How can we ensure users' SIM identities are secure and private in an eSIM environment? Can such a system provide data services in the same manner as voice and SMS? This paper has focused on the initial proof of concept system-building aspect of providing a solution. We leave the open questions for future work.

An outstanding challenge relates to the coverage we extend. PhoneHome relies on a remote node located within the coverage area of a carrier. The placement of the node is likely to be chosen based on ease of access to the area and the constraints of building a long-distance link to the node. What we do not account for, however, is the capacity of the infrastructure our remote node utilizes. That is, we may be introducing a load that the existing infrastructure was not designed to handle. We are exploring load-balancing across multiple commercial base stations to address this issue.

We have presented PhoneHome, a prototype system that extends existing cellular coverage on a community scale without requiring traditional wireless infrastructure investment. Our system is specifically designed for areas where existing coverage is inadequate for the local population, such as refugee camps or post-disaster shelters. Millions of people now live at, or beyond, the margins of traditional cellular coverage because they were forced to leave their homes due to man-made or natural disasters. PhoneHome provides a critical solution for facilitating communications for such people in a time when they need it most.

VIII. ACKNOWLEDGEMENTS

This work was funded through NSF Network Science and Engineering (NetSE) Award CNS-1064821 and NSF Catalyzing New International Collaborations (CNIC) Award IIA-1427873.

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