Kwiizya: Local Cellular Network Services in Remote Areas

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ABSTRACT

Cellular networks have revolutionized the way people communicate in rural areas. At the same time, deployment of commercial-grade cellular networks in areas with low population density, such as in rural sub-Saharan Africa, is prohibitively expensive relative to the return of investment. As a result, 48% of the rural population in Africa remains disconnected. To address this problem, we design a local cellular network architecture, Kwiizya, that provides basic voice and text messaging services in rural areas. Our system features an interface for development of text message based applications that can be leveraged for improved health care, education and support of local businesses. We deployed an instance of Kwiizya in the rural village of Macha in Zambia. Our deployment utilizes the existing long distance Wi-Fi network in the village for inter-base station communication to provide high quality services with minimal infrastructure requirements. In this paper we evaluate Kwiizya in-situ in Macha and show that the network maintains low delay and jitter (20ms and 3ms, respectively) for voice call traffic, while providing high call Mean Opinion Score of 3.46, which is the theoretical maximum supported by our system.

Categories and Subject Descriptors

C.2 [**Computer-communication networks**]: Network architecture and design; C.4 [**Performance of systems**]: Design studies

Keywords

Mobile telephony, Rural area networks, Low-cost communication, OpenBTS, Cellular communication

1. INTRODUCTION

It is clear that mobile phone usage has become one of the most prevalent means of communication worldwide. 2011 statistics from the International Telecommunication Union indicate that, worldwide, there are 85.7 mobile-cellular subscriptions per 100 inhabitants [13]. This number has been steadily increasing over the last 10 years, with growth over the last five years primarily driven by subscriptions in the developing world.

While the statistics are encouraging, what they mask is the huge differential in cost and service availability and quality between the developed and the developing world. For instance, while residents of developed countries spend on average 2% of their monthly income on cellular service, the cost in developing countries is closer to 12% [13]. In addition, the ability of residents in developing regions to access cellphone technology is reduced by limited cellular deployments; while many residents own phones and buy either subscriptions or pre-paid plans, coverage may be spotty or non-existent within residential areas of low population densities[1], as is characteristic of the majority of the world's rural developing regions. Further, while 4G is rapidly becoming available throughout the developed world, in developing regions coverage is often limited to 2G, or 2G + EDGE at best. This discrepancy hints that despite technological advancements, there will always exist an economic challenge in deployment of high-end cellular technology in sparse rural areas. Thus, there will be recurring need for lower cost solutions to serve those areas.

Despite these limitations and high costs, mobile phones are critical for providing communication in developing regions due to limited or non-existent telecommunications infrastructure and poor roads, making quick distance travel difficult. In many developing communities, cultures are oral – communication is based on oral, as opposed to written, forms. Storytelling in such communities is vital to forming world views, maintaining trans-generational knowledge and teaching practical skills. Further, oral communication facilitates practical information exchange, such as crop prices, health care availability, and numerous others. In our own fieldwork in Macha, Zambia, we have witnessed that cellphone availability combined with Internet access can enable rapid information dissemination, whereby person(s) with Internet access serve as information gateways to other, disconnected interested parties.

Our work is in partnership with the LinkNet organization in Macha, Zambia. Our team has visited Macha over the past three years, most recently spending three weeks in the Macha community during June/July 2012. During these visits, through both informal conversations and structured

[1]The World Bank 2012 report on "Maximizing Mobile" notes that mobile network operators find it commercially infeasible to operate in rural areas.

MobiSys'13, June 25-28, 2013, Taipei, Taiwan

interviews, we have learned first hand of the deep desire of local residents for better cellular access. While every resident we encountered owns a cell phone, few have coverage at their homes. In fact, many residents own multiple phones to leverage any available coverage they come across as they travel. Further, the cost of cellular access is prohibitive. Residents rely on pre-paid access cards, which they can afford at unpredictable times due to unreliable income streams. Even the cost of frequent SMS is out of reach for many residents. Yet, the residents have enough experience with this technology to appreciate its value; 100% of our interviewees expressed a desire for better, more affordable cellular access. As a result of these costs, call durations are short, and conversations are quick and to the point. Many users simply carry phones, waiting for someone to call them, as incoming calls are free in the current cost structure.

Studies of locality of interest [14, 20] indicate that communication through technology largely appears between individuals in close physical proximity. Onnela et al. analyzed 72 million calls and 17 million text messages in Europe and found that probability of communication decreases by 5 orders of magnitude when distance between communicating parties increases from 1km to 1000km [20]. Our own prior work has demonstrated the propensity of rural users to communicate with those physically nearby: Facebook Instant Message analysis in Macha showed that, while only 35% of observed users were in the village, 54% of instant messages were between local users [14]. These statistics emphasize the need for solutions that support local voice communication in remote areas.

To address the lack of reliable and affordable cellular coverage in remote communities, we have endeavored to create a cellular access system that facilitates free local calls and SMS within a community. Our system, Kwiizya[2], leverages open-source software solutions, such as OpenBTS[3] and FreeSwitch[4], to provide local voice and text messaging services. In our recent trip to Macha, we deployed two Kwiizya instantiations and gave pre-registered SIM cards to project partners. As a result, we have had the opportunity to assess usage in a fairly unregulated, in-situ scenario. In an earlier work we outlined VillageCell, an idea for providing local calls within a community [5]. In contrast, our current solution utilizes different open-source software components, offers SMS and IM-to-SMS functionality, has been fully deployed and tested in-situ in Macha, Zambia, and opened to a set of test users in Macha.

This paper makes several contributions:

- design and integration of a *low-cost* cellular network alternative that is well suited for local communications in remote rural communities,
- evaluation of a fully operational instance of our system deployed in the field,
- modification of OpenBTS to support Instant Message to SMS functionality for SMS-based applications,
- evaluation of our platform for SMS-based applications, and
- discussion of infrastructure and sustainability-related aspects of alternative cellular network deployments.

[2]Kwiizya means "to chat" in Tonga, the native language in Zambia's Southern province.
[3]`http://wush.net/trac/rangepublic`
[4]`http://freeswitch.org/`

We begin by describing the current state of rural telephony in our partner communities, including results from our detailed interviews with Macha residents. We then describe the Kwiizya architecture, including voice and SMS functionality. In section 5 we describe our deployment within Macha, including some of the deployment challenges we faced in this remote community. We describe results from controlled field tests, as well as results from public usage, of Kwiizya in section 6. Based on our performance analysis and our experience in Macha and in maintaining the system remotely, we offer our thoughts for improvement and some general guidelines for work in remote regions in section 8.

2. VOICE COMMUNICATION IN RURAL ZAMBIA

Voice technologies are revolutionizing communication in remote areas. For example, access to cellphones in Macha allowed farmers to overcome what they call the "briefcase buyers problem", whereby businessmen who buy maize come to the village and often attempt to exploit farmers who are unaware of market prices, buying crops at extremely low prices. Farmers in Macha can now call the Zambian Food Reserve Agency (FRA) to get information about crops prices. Furthermore, a new communication structure of a combination of Internet and cellphones has emerged in Macha, whereby a farmer who has access to both the Internet and a cellphone can check crop prices online and send text messages to fellow farmers.

During our field work in Zambia, we visited Macha and three surrounding villages – Hamoonde, Chikanta and Mapanza. All of these villages use VoIP, cellular technology or both as a means for voice communication. Within the four communities the level of availability of these technologies varies widely, resulting in fundamentally different voice communications usage patterns. We summarize the current cellphone coverage and usage in these communities below.

Macha. Macha is a village in the Southern province of Zambia, located 70km from the closest city, Choma. There are 135,000 people in the area spread over a large radius of 35km. The village is connected to the national power grid; however, individual households rarely have access to electricity. This sparse availability of power results in creative solutions, such as travel to powered public spaces to charge cellphones; others charge their phones while at work. However, while power is technically available, the reality is that the availability and quality can vary on an hourly or daily basis.

Cellphone coverage in Macha was first introduced in 2006 by Celtel (now Airtel). By 2012, MTN was a second active cellphone provider in the village. Residents with a cellphone subscription can use plain voice and text messaging and, where available, low data rate GPRS service for Internet access. The coverage provided by the two operators is largely available in the central part of the village; coverage is inconsistent and spotty in residential areas. A large percent of the people we interviewed had subscriptions with both cellular providers to increase the likelihood they have cellphone coverage at any given time. Our first hand and anecdotal experience, however, indicates that the failures of both commercial networks are highly correlated and often coincide with power failures.

In terms of VoIP, Macha is connected to the Internet through one of Zambia's Internet service providers. A monthly subscription limited at 1GB traffic costs 30 USD. Together with electrical unavailability, this high price renders home Internet access impossible for most residents. A small subset, however, can access the Internet from work or from an Internet café in order to use VoIP services.

Hamoonde. In contrast with Macha, neighboring Hamoonde, only 5km away, has very sparse cellular coverage, no Internet access and no connection to the power grid. Villagers identified the lack of electricity as the main obstacle to computer and Internet access in the village. People we spoke with, however, owned cellphones and expressed their desire to have more widespread cellular coverage. Residents carry their phones for use when they enter an area where cellular access is available. We encountered a case where a cellphone was used as a voice gateway to the Internet, whereby one resident of the village regularly called a relative in the city with access to the Internet to ask her to lookup information online.

Chikanta. Chikanta has population of about 40,000 and is 25km away from Macha. There is no access to electricity within the village; commercial cellphone coverage was introduced in some areas of the village in the beginning of 2012. A commute of 2km is common for village residents to reach an area with cellphone coverage. Interestingly, Chikanta has been largely influenced by the technological innovations within Macha. In 2010, two years before commercial cellular coverage was available in the village, Chikanta obtained an Internet container kiosk[5] that connects the village to the Internet through a satellite link and that runs on solar power. This allowed people from the village to start gaining experience with VoIP before they had easy access to cellular technology.

Mapanza. Mapanza is 7km away from Macha and has population of about 2000 people. There is cellphone coverage in the central part of the village. Similar to Chikanta, Mapanza recently obtained an Internet container kiosk that operates as an Internet café and uses a slow satellite link to connect to the Internet.

3. SOCIAL SURVEYS

During our three week field trip to Zambia in June/July 2012, we conducted extensive interviews with local residents to better understand their usage and experience with voice communication technologies. Each interview was conducted privately with one interviewee, one interviewer and a translator if necessary. Part of the interview questions were of closed form (pre-selected answer options) while others were open ended to enable free discussion of voice communication topics. Interview participation was voluntary and no material incentive was associated with participation. While our method did not produce a random sample of interviewees, we made an effort to interview people across age, gender, occupation and income groups.

In the course of three weeks, we interviewed 26 people total from Macha, Hamoonde and Chikanta. Our interviewees were between 20 and 48 years old; 14 were female and 12 were male. All had owned a cellphone at some point; 96% owned a phone at the time of the interview. Those who did not wanted to recover access but did not have money to do so. People who owned a phone either bought the phone themselves (76%) or obtained it as a gift. Despite the high availability of cellphones among the group we interviewed, cellphones are very expensive relative to income; 68% of phone owners who bought their phone had to save between one month and one year to afford to buy that phone. Our interviewees shared that apart from buying the cellphone, the recurring cost for air time significantly adds to the financial burden for adoption of cellphone technology.

44% of our interviewees had more than one SIM card and most often identified one of two reasons for their subscription with multiple cellular networks. The first reason is associated with cost; inter-provider services cost more in comparison to intra-provider services. Thus, users often carry more than one SIM card and pick the one to use based on the network to which the person they are calling is subscribed. The second most popular reason for people having multiple SIM cards is reliability. As the quality of service often varies over time and space, users carry multiple SIM cards to increase the chance they will be able to use a cellphone network at any time. Despite this effort, a commute of 1-2km is typical for residents of Hamoonde and Chikanta to reach to an area with coverage and conduct a call.

When asked what is enjoyable about cellphone usage, 100% of our interviewees identified the opportunity to stay in touch with relatives, including those who live in other places. 80% indicated that they use the phone to obtain information, such as crop pricing for farmers, availability of goods for local businessmen who buy from the city and communication with regional authorities. Users with more advanced phones and data subscriptions identify the importance of staying connected to the Internet at all times. With the low rate GPRS connection in Macha, however, all users with cell phone Internet access indicated that browsing is slow and frustrating.

Our interview findings confirm the importance of cellphone technology for residents of remote areas. While the reasons for adoption of cellphone technology are not drastically different than these in the western world, the benefits for people in remote communities without infrastructure and with intermittent income is much more pronounced. Obtaining information via cell phone, as opposed to in person after travel, saves both critical time and money. Unfortunately, while the benefits and need of cellphone technology in remote areas are well understood, wide availability and affordability of such technology is still severely lacking.

4. KWIIZYA

Kwiizya is a low-cost cellular system that leverages existing, unmodified mobile phones and SIM cards to provide voice and text messaging for free within the network. We envision Kwiizya as an underlying infrastructure for low bandwidth applications that make use of short text messages and therefore enhance Kwiizya with functionality that enables such applications. In the following section we describe the voice and text messaging operation of Kwiizya, present the integration of Kwiizya's core components, and discuss the extensions we have implemented to facilitate SMS applications.

[5]http://www.machaworks.org/en/projectwizard.html/project/25

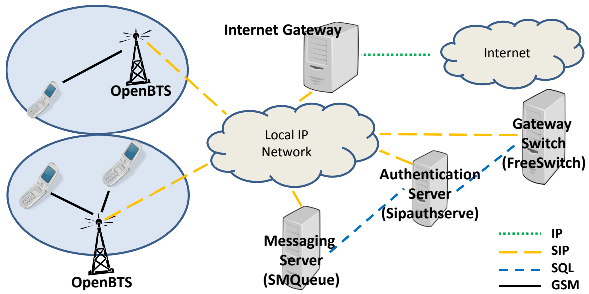


Figure 1: Kwiizya architecture.

4.1 Architecture

Depicted in Figure 1, Kwiizya utilizes free open-source software to provide voice and text message services. The base stations run OpenBTS, which implements the GSM stack and communicates with the associated cellphones using the standard Um radio interface for commodity 2G and 2.5G cellphones. OpenBTS is also responsible for translating GSM messages to SIP, which allows the use of low cost generic IP backbone infrastructure as opposed to an expensive commercial-grade GSM backbone. SIP translation enables the use of free VoIP server software to serve as a Mobile Switching Center for routing calls.

To route calls within and outside Kwiizya, we use FreeSwitch. FreeSwitch connects to OpenBTS via SIP and RTP and routes calls both in intra- and inter-BTS local scenarios. It has the capability to route calls outside of the network to commercial cellular, fixed line and VoIP networks using SIP and SS7. By the means of custom python scripts, FreeSwitch allows extension of the basic routing functionality to facilitate cellphone based applications. We describe in more detail the specific extensions we have implemented in section 4.2.

Kwiizya utilizes Sipauthserve and SMQueue to handle user authentication and text messaging, respectively. SMQueue is the SIP-based equivalent of an SMSC (Short Text Messaging Central) in a commercial-grade system. As such it interfaces with OpenBTS and makes use of commodity IP networks to transmit SMS (Short Message System). At the same time it can interface with commercial SMSCs using SS7 and SMPP. SMQueue implements a store and forward SMS queue functionality that allows messages to be delivered in a delay tolerant fashion. The latter is of great importance for areas with intermittent cellphone access and electric power availability as users are often either out of range or have their cellphone powered off. To handle user authentication and mobility, Kwiizya leverages Sipauthserve – a database server with an interface to process SIP REGISTER messages to track mobility. Both SMQueue and Sipauthserve are queried by other network elements (e.g. FreeSwitch and OpenBTS) through SQL.

4.2 Support for SMS-based applications

Because cellphone communication is an increasingly popular method for residents of remote areas to stay connected, cellphones are widely used for applications other than plain voice and text messaging. Low data rate applications that leverage 160-symbol text messages have been utilized in education [15, 24, 25], web browsing [8], agriculture [9, 22, 23] and health care [6, 10, 11, 16, 21].

In the design of Kwiizya we are inherently interested in enabling functionality that will support such applications. Beyond simple SMS, we need functionality that supports SMS broadcast and multicast, and in particular does so through an Instant Message (IM) interface. Our IM-SMS interface enables fast typing and rapid outreach to a large set of subscribers. This interface has a wide variety of uses. For instance, a health worker could use it to notify subscribers of a change in health post hours of operation, or of the availability of particular vaccinations during a health scare. Our solution exposes an API that allows development of applications that can leverage the text broadcasting functionality to automate message generation, obviating the need of an actual person to send IM messages. This capability facilitates a variety of automated services, such as automatic weather alerts, dissemination of crops prices, and health care availability updates. Our design unifies this IM extension with SMS to enable rapid distribution of instant messages from any packet data network. This unified mode of messaging is asynchronous by design to minimize resource waste and guarantees only best effort delivery. We have identified four key design considerations for such a unified mode of messaging to work seamlessly with Kwiizya in a rural setting:

- A small memory footprint of the IM client on the host device; the client is designed to work on unmodified commodity hardware available in rural areas.
- Usability across various operating systems to target a heterogeneous set of devices.
- Capability of exchanging packet data with Kwiizya remotely over the Internet.
- Ability to leverage the existing SIP switching/routing capability available in FreeSwitch to enable easy and accurate routing of IM messages to Kwiizya users in the form of SMS and vice-versa.

We implement our IM client using the open-source multimedia communication library PJSIP[6]. PJSIP implements the SIP protocol stack and supports all three NAT traversal functionalities, i.e. STUN, TURN and ICE. This facilitates routing of SIP traffic from various networks, including private IP networks such as home, office and enterprise LANs. It also exposes all functionality in suitable APIs for a wide variety of systems, including desktop and smart phones, and meets the key design goals identified above.

Figure 2 presents a typical usage scenario of our IM client. The client needs to be installed on a machine that can access the Kwiizya core network. The IM client then communicates directly with FreeSwitch when sending text messages to users associated with Kwiizya. FreeSwitch handles the delivery of a text message to the end user.

Provisioning a new user for Instant Messaging: Any new user of the IM service is manually provisioned with a valid SIP address of record [26] in the Kwiizya Subscriber Registry (Sipauthserve on Figure 2). An IM user in Kwiizya is identified by their SIP address of record (SIP user identity) and unique phone number. The SIP identity is used by internal subsystems in Kwiizya, i.e. FreeSwitch, SMQueue and OpenBTS, to validate and route any SIP traffic related to a particular IM user. The IM client's phone number is exposed to the other cellphone users of Kwiizya, so that the

[6] http://www.pjsip.org/

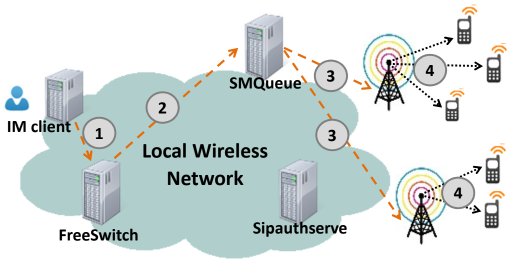
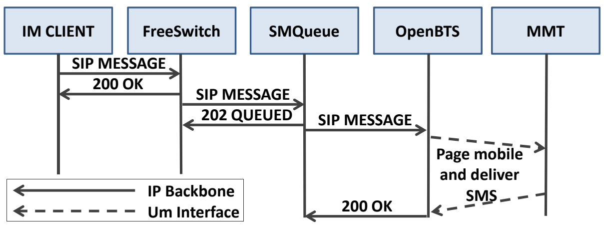
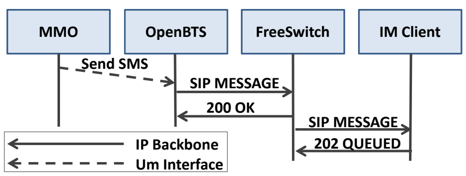


Figure 2: IM-SMS system architecture.

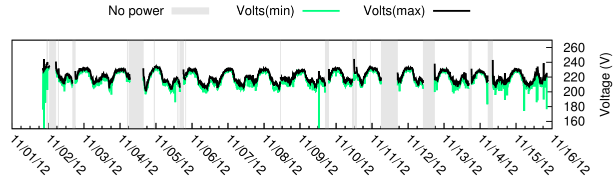


(a)

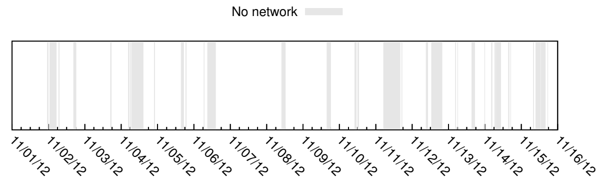


(b)

Figure 3: Message exchange between Kwiizya entities to send a SMS (a) from the IM client to a Kwiizya subscriber and (b) from a Kwiizya subscriber to the IM client.



(a)



(b)

Figure 4: Power and network quality in Macha.

sender of a message can be identified and the recipient can respond if needed. To reach the IM client, Kwiizya also stores the IP address of the host where the IM client is installed. Currently, this necessitates an IM user to utilize the IM service only from a pre-provisioned host address. This mechanism, however, can later be extended to a dynamic address binding scheme.

Routing an IM message: As illustrated in Figure 3(a), upon sending a message to a Kwiizya user (Mobile Message Terminator – MMT), the IM client generates a standard SIP MESSAGE request [7], that contains the message in plain text format as well as the SIP address of record of the recipient. This SIP MESSAGE is then sent to FreeSwitch, which forwards it to SMQueue after validating the identity of the sender. SMQueue stores the message in its store-and-forward queue and attempts best effort delivery to the Kwiizya base station where the recipient is registered. Because the entire SMS functionality in Kwiizya is asynchronous, a real time session is not required for transmission of the IM message to its recipient. This design makes Kwiizya messaging particularly suitable for rural environments, where a user is not likely to be associated with the network at the time the message is sent. If the user is not associated, SMQueue stores the message and regularly attempts delivery. This design avoids waste of resources typically associated with synchronous/session based messaging.

Our design enables a cellphone user (Mobile Message Originator – MMO) to send a message to a provisioned IM client using the SMS interface available in a legacy GSM phone. After receiving a SMS destined to an IM user, a Kwiizya base station constructs a new SIP MESSAGE request with the SMS content attached as a SIP message body in the SIP request and forwards it to FreeSwitch (Figure 3(b)). After validating that both the sender and the receiver are provisioned in Kwiizya, FreeSwitch sends a new SIP MESSAGE request to the IM client's host using the IP address it stored earlier in the Kwiizya Subscriber Registry. This exchange of messages between a Kwiizya user and an IM user also occurs asynchronously between all the participating entities.

5. MACHA DEPLOYMENT

During our trip to Macha in June/July 2012, we deployed an instance of Kwiizya. We chose Macha for our first field deployment, even though commercial cellphone coverage is available in the village center, because Macha is fairly well connected in terms of Internet access. This allows us to have remote access to our system for administration and performance evaluation purposes. In the following sections, we detail challenges we faced, many of which are not found in developed world deployments. We then describe how these challenges influenced our system deployment.

5.1 Design challenges

Power. Our Kwiizya base stations require 12VDC and draw a maximum of 3A, which can be supplied by a 12V power transformer powered by the main grid. Our deployment locations are connected to the national power grid; however, the quality of power varies drastically over time as shown in Figure 4(a). The figure represents a sample two week period. The x-axis of Figure 4(a) plots time in days and the y-axis plots voltage. The gray areas on the plot indicate periods of power outage. We measure power quality in Macha sampling every second; each plotted voltage value corresponds to five minutes and presents the minimum (green line) and maximum (black line) measured voltage within these five minutes. The supplied voltage in Zambia should be 220V; however, as Figure 4(a) indicates, the voltage varies from 150V to 240V with frequent power failures. Furthermore, there are long periods, for example November

(a) (b)

Figure 5: Our equipment in Macha: (a) the base station and (b) the power supply.

15 and 16, of power brownouts in which electricity is available, but the voltage is continuously low. This is particularly harmful for computer equipment. Voltage tends to follow a diurnal pattern, typical for a system that is overloaded; the power quality is particularly poor during the day when the utilization of the power grid is higher. This poor power quality is harmful to equipment and makes remote access for administration and evaluation extremely challenging.

Internet access. The remote accessibility of the system is not only influenced by power availability but by network availability as well. Power is often available in the village; however, due to an outage in the upstream link, the village gateway cannot connect to the Internet. Figure 4(b) shows network availability over the same two week period in November. In comparison to power outages, there are many more network outages, which further reduce our ability to access Kwiizya remotely.

Logging and storage. Logging is important for system administration and troubleshooting; however, special attention should be paid when enabling logging to ensure it does not deteriorate system performance, as writing to disk can slow the system. We experienced an event where a combination of detailed logging and limited storage in the base station caused Kwiizya to malfunction.

We adapt our system design to meet these challenges. The following section provides technical details about our field deployment.

5.2 Technical details

Our Macha deployment operates in the GSM-1800 band. We chose this band for two reasons. First, most residents have basic dual band (900/1800) phones, so the use of GSM-1800 maximizes the number of people who will be able to use the system with their existing phones. Second, GSM-1800 does not interfere with commercial cellular providers, which operate at GSM-900 in rural areas.

Kwiizya consists of two self-contained RangeNetworks base stations[7] (Figure 5(a)), each of which covers a radius of up to 3km. Each base station unit includes a software-defined radio, a 1W power amplifier, a duplexer, and a small integrated PC with 4GB flash card that runs Ubuntu 10.04. Each unit can independently run all components of a GSM network. However, to scale the network to a wider physical area, we use one of the base station PCs as a network central server, running FreeSwitch, Sipauthserve and SMQueue; the second base station runs only OpenBTS and connects to the first one (Figure 6) for all other services. The connection between the two base stations is facilitated through a long

[7] `http://rangenetworks.com/`

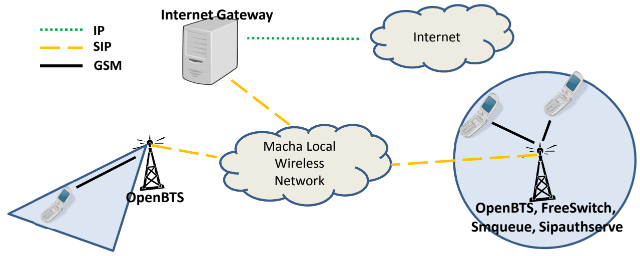


Figure 6: Kwiizya deployment in Macha.

(a) (b)

Figure 7: Kwiizya sites in Macha: (a) the water tower and (b) LITA.

distance Wi-Fi link that was readily available through the local wireless network in Macha.

To handle the problem of limited storage we attach a 1TB external hard drive to each base station. We check the internal disk utilization periodically and when it reaches 90%, we offload syslogs from the base station PC onto the external hard disk to free disk space and save logs for future reference. We use simple ping based monitoring to inform us when access to the village gateway is available from the outside, so that we can analyze network availability and know when our logs are accessible.

Determination of the most suitable power supply to resist the power fluctuations in Macha while providing stable 12V/3A to our base stations was an iterative process. We started with a complex of deep cycle car batteries and car battery chargers; however, within ten days we lost one charger due to poor power quality and two of the batteries started leaking due to overcharge. Eventually, we changed our power supply to the one shown in Figure 5(b), which includes a UPS, a 5A/12V monitor power supply and a wooden block with nails to keep the power cable terminals in place, so they do not short out.

The area of Macha is relatively flat with small hills, so providing coverage was a matter of installing the base stations on elevated locations. We installed one of the base stations on a 30m water tower with a 10m communication mast on top (Figure 7(a)). For this site we used an 11dBi omni directional antenna. Our second base station was installed close to the LinkNet IT Academy (LITA) on a 12m mast mounted on the ground (Figure 7(b)) and used an 11dBi 90 degree sector antenna. The distance between the two sites is 2.3km; each site is capable of providing coverage in up to 3km radius depending on terrain.

While Kwiizya supports open registration with existing cellphones and SIM cards, we opted for restricted registration during our initial field testing. We manually provisioned 20 SIM cards and distributed the cards to a small set of users comprised by our local partners and their families. This allowed us more control during the initial performance evaluation of our system, while still allowing our users unrestricted access. In the near future, we plan to deploy Kwiizya in neighboring communities with no existing cellphone coverage and enable open registration.

We placed two GSM modems in the field, which allows us to send SMS and conduct calls in the Kwiizya network in a controlled manner. We chose U-Blox quadband GSM/GPRS modems that can be powered and controlled through USB. The latter is important because it allows the modems to be powered by the server to which they are connected, thereby making them independent of an individual reliable power supply. We attached the modems to an Ubuntu server and were able to access and control them remotely using AT commands, which are a suite of specialized commands for remote control of GSM modems.

Each call in Kwiizya has two associated VoIP sessions – one for the mobile call originator (MCO) and one for the mobile call terminator (MCT). A VoIP session consists of a SIP control session and forward and reverse RTP streams that carry the actual voice traffic. The Kwiizya deployment in Macha supports four call scenarios depending on the locality of the MCO and the MCT. We describe these call scenarios in turn:

- *Water tower – Water tower.* This is a call scenario where both the MCO and the MCT are in the vicinity of the water tower base station. This setup does not utilize the backhaul wireless link; both VoIP sessions are established only through the water tower base station.
- *Water tower – LITA* and *LITA – Water tower.* In the first scenario, the MCO is associated with the water tower and the MCT with LITA; the opposite holds for the second call scenario. These two scenarios are identical in terms of resource utilization. In each of the cases one of the VoIP sessions utilizes the backhaul link and the other one is local at the water tower.
- *LITA – LITA.* In this case both the MCO and the MCT are attached at LITA. In this scenario, both the MCO and MCT VoIP sessions traverse the wireless backhaul.

6. EVALUATION OF KWIIZYA

Our evaluation of Kwiizya includes two parts – (i) controlled experiments and (ii) evaluation of system usage in the wild following our Macha deployment. Our controlled experiments take place in two testbeds: one located in our lab in UCSB and one in Macha. We first evaluate Kwiizya by running a number of controlled experiments that test the system's ability to provide services and the quality of these services. The second part of our evaluation assesses the actual deployment experience.

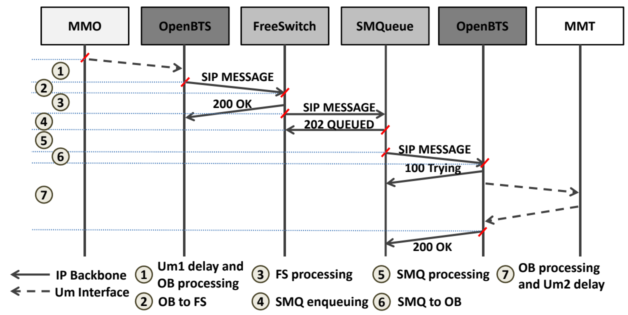


Figure 8: SIP messages transmission of a SMS from MMO to MMT.

6.1 Controlled experiments

We focus our controlled experiments on three aspects of the system: (i) text messaging, (ii) voice calls and (iii) instant messaging to SMS. In the process of evaluation we take into account OpenBTS' capabilities as well as limitations of the GSM modems to ensure the accuracy of our performance measurements. First of all, OpenBTS can handle at most 84 SMS messages per minute and 7 simultaneous calls, so we ensure we do not generate traffic at a higher rate so that delay and call quality are accurately measured. Furthermore, the GSM modems incur a delay of about 0.5 seconds to execute the commands associated with sending a single message. Finally, there needs to be an inter-message delay of 6 seconds to ensure the GSM modem does not become overloaded with outgoing messages. When overloaded, the modem fails to send messages to Kwiizya.

We conduct our controlled experiments in two testbeds, one located in our lab at UCSB and one located in Macha. Our lab setup includes one RangeNetworks SNAP unit, the same as the ones deployed in Macha. The unit operates as a self contained system running all four services – OpenBTS, FreeSwitch, Sipauthserve and SMQueue. Our testbed in Macha includes the base station installed at LITA and a second base station inside the IT room. The indoor base station runs FreeSwitch, Sipauthserve and SMQueue. LITA runs only OpenBTS and connects to the indoor base station for the other services. In this test setup we utilize the readily available network infrastructure in Macha to connect the two base stations. As a result, we use an existing wired connection for the backbone link between the indoor installation and LITA. All Kwiizya components are strictly time synchronized. This is achieved using NTP, where all machines in Kwiizya synchronize to a local server to maximize accuracy.

6.1.1 SMS and Voice Calls

To evaluate SMS and voice call quality through controlled experiments we use our testbed in Macha. We deploy two U-blox quadband GSM/GPRS modems in Macha and associate them with the LITA base station. Both modems are connected to a server that can be accessed from the Internet. We then automate SMS and voice calls between the two modems.

We evaluate the end-to-end delay for delivery of a single message and assess the delay components incurred by each element of Kwiizya. Figure 8 gives an overview of the SIP message exchange associated with delivery of a single

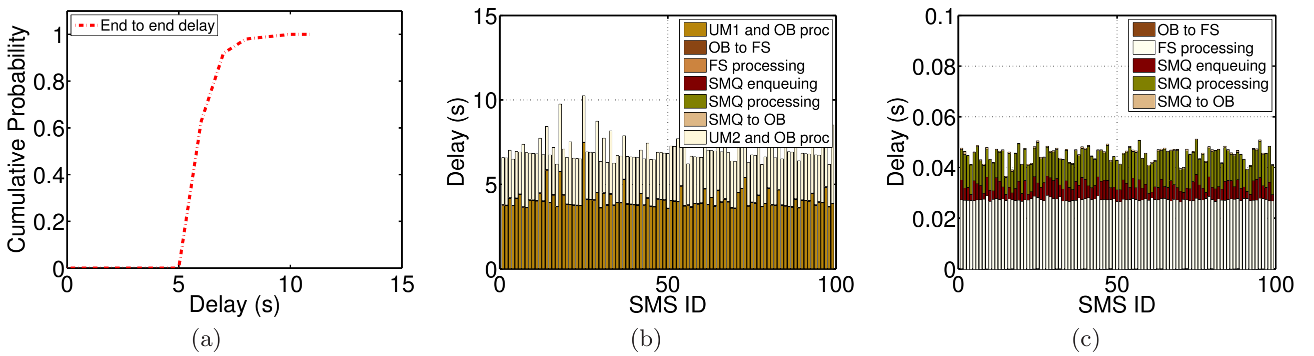


Figure 9: Evaluation of 100 SMS transmissions to associated users. (a) CDF of end to end delay; (b) breakdown of delay components per message; and (c) zoom of non-Um delay components.

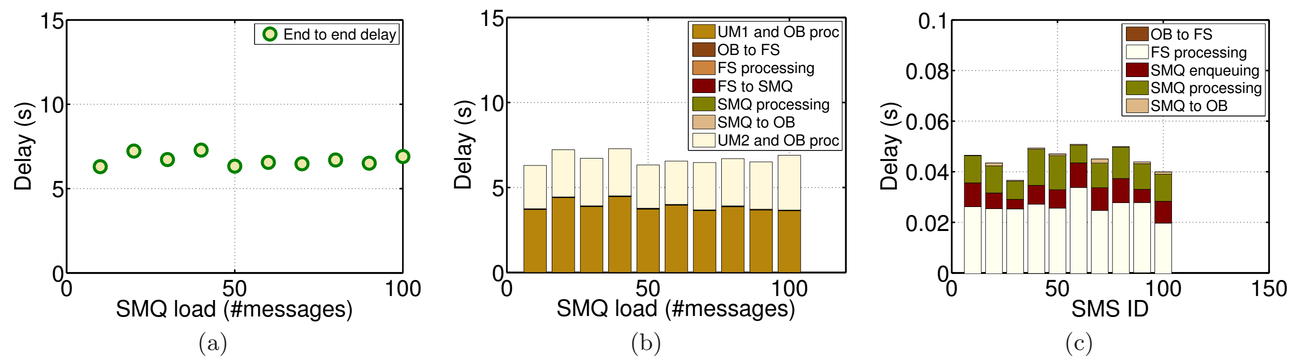


Figure 10: Impact of increasing SMQueue load on (a) the end to end delay; (b) the delay components; and (c) non-Um delay components.

SMS from a Mobile Message Originator (MMO) to a Mobile Message Terminator (MMT). If two components are coded with the same color, they run on the same physical machine. The figure also presents our approach to calculating the delay components. We calculate the end to end delay as a sum of each extracted delay component.

In our evaluation of SMS delivery we focus on two scenarios. First, we evaluate delay for delivery of messages to users associated with the network. We then evaluate the impact of SMQueue load on the end-to-end delay by increasing the number of transmitted messages to users that are provisioned but not associated with the network. The latter increases the load of pending messages in SMQueue. We then measure the time it takes for a message to be received by a registered user.

To evaluate the delay for message delivery to a user associated with Kwiizya, we sent 100 consecutive messages, with 6 seconds inter-message delay. 99 of these messages were received by Kwiizya; one message failed to depart from the sending GSM modem. Of the 99 messages that entered Kwiizya, all 99 were successfully delivered to the receiving modem. Figure 9 presents our results. In Figure 9(a) we plot a CDF of the end to end delay. As the graph shows, 99% of the messages were delivered to their destination in $6-9$ seconds; the maximum observed delay is 11 seconds. The average delay over all 99 messages is 7.06 seconds with standard deviation of only 0.7 seconds. Figure 9(b) presents a breakdown of delay incurred by the separate Kwiizya components for each text message. The major contributors to the end-to-end delay are the radio interfaces from the MMO to OpenBTS (Um1) and from OpenBTS to the MMT (Um2). Figure 9(c) shows a zoom of the delays of the non-Um components of Kwiizya. The contribution of the non-Um components together is at most 50ms with average over all messages of 45.4 ms. This performance is persistent over different messages, as the standard deviation for non-Um delay is only 2.9 ms.

Where users do not have continuous access to Kwiizya, the network stores text messages and aggressively attempts to deliver them every second. This incurs overhead in SMQueue in storing messages and reattempting delivery. We evaluate the impact of this overhead on the end to end delivery delay of messages to registered users. We increase the SMQueue load from 10 to 100 messages in steps of 10. At each step we send one message to a registered user and measure the delivery delay for this message. As Figure 10(a) shows, the end to end delay does not increase with the number of enqueued messages; thus it is not dependent on the SMQueue load for as much as 100 enqueued messages. This observation is further confirmed by Figures 10(b) and 10(c), which show delay components for each of the 10 delivered messages. Once again, Um1 and Um2 are the largest contributors to the end-to-end delay. Furthermore, each of the ten messages is delivered in less than 8 seconds, which is within the average delay range encountered on Figure 9(a).

Finally, in our test setup in Macha, we measure the call establishment time. As depicted in Figure 11, this is the time from when the first SIP INVITE message is sent by the MCO base station (informally from when the calling party hits “dial”) to when the MCT starts ringing (or when the calling party starts hearing the “ring” tone). Again compo-

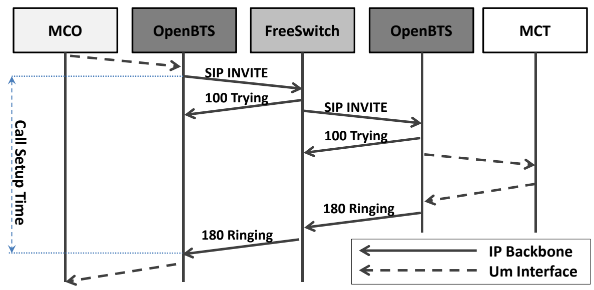


Figure 11: Call setup SIP message transaction.

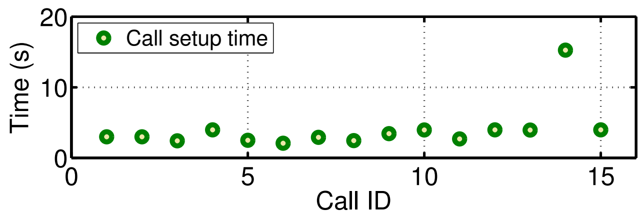


Figure 12: Call setup time.

nents with the same color run on the same physical machine. We run an experiment with 15 consecutive calls. Figure 12 presents our results; call ID is plotted on the x-axis and call setup delay in seconds on the y-axis. The figure indicates that with one exception, it typically takes between 2 and 4 seconds for a call to initiate. We examined the delay components of the outlier call 14; the 15 second setup time is caused either by delay in the Um radio interface between OpenBTS and the GSM modem or by a glitch in the GSM modem itself. We leave the evaluation of call quality to the calls placed by actual users; our findings are described in section 6.2.

6.1.2 Instant Messaging to SMS

As detailed in section 4, we extend Kwiizya's basic cellular network functionality to provide a platform for development of applications that utilize text messaging. This platform delivers an interface between an instant messenger and the cellular network and enables burst message transmission to users registered with the network.

We evaluate our Instant Messaging to SMS (IM-SMS) functionality in our lab setup at UCSB. We perform this evaluation at UCSB because of the need for multiple test receivers, for which we did not have the capacity in Macha. We installed our IM client on a server, running Ubuntu 12.04. We associate three HTC G1 phones with the test network to act as receivers during our experiments.

We conduct two sets of experiments to evaluate the end to end delay for message delivery from the IM client to users in Kwiizya. We also calculate the delay imposed by each Kwiizya component. Figure 13 presents the SIP message exchange for delivery of a SMS and breaks down each delay component. Again components that run on the same physical machine are coded with the same color.

Our first experiment evaluates the time for message delivery when the IM client sends bursts of messages to *associated users*. In particular, we are interested in the implications of the burst size on the end to end delay. We send bursts of messages of increasing size from the IM client to three users

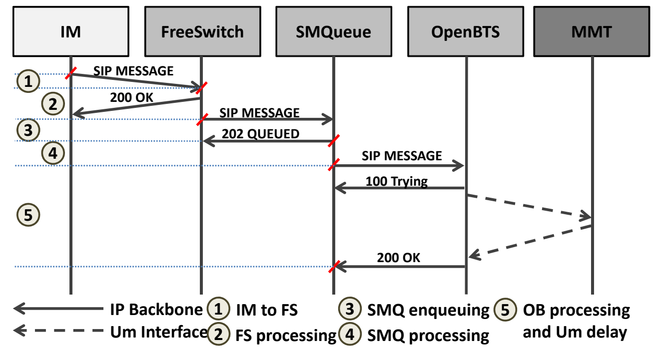


Figure 13: SIP messages transmission of a SMS from IM to a Kwiizya user.

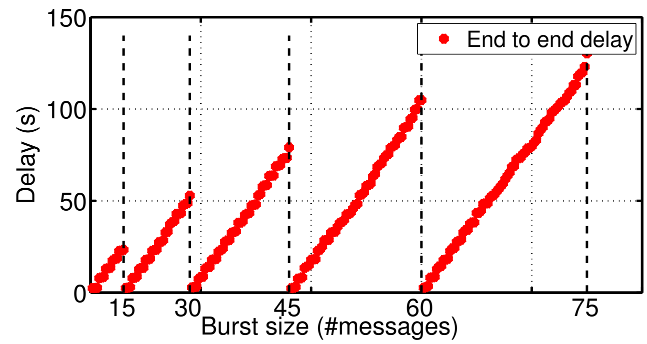


Figure 14: IM-SMS end to end delay when sending to registered users.

associated with Kwiizya with inter-burst time of 60 seconds. At each iteration 1/3 of the burst is sent to each of the receivers. It is important to note that each phone can only receive one message at a time. Thus, if five messages are sent simultaneously to the same phone, the first message should arrive in X seconds, the second in $2X$ seconds and so on. In our IM-SMS tests we used three phones to receive bursts ranging in size from 15 to 75 messages. Every message sent in this experiment was received at its destination.

Figure 14 plots burst size on the x-axis and end to end delay on the y-axis. Each point on the plot corresponds to delay for a single message and each vertical line indicates the burst size. In each segment of the graph there are $burstSize/3$ well established groups, each of which contains three plotted values, one for each receiver. On the plot these three values appear overlapped, which indicates that message delivery to all three phones is approximately the same. This separation in groups is due to the increasing delay for delivery of a burst of messages to the same user. Messages across different burst sizes take the same amount of delivery time, which demonstrates that Kwiizya is capable of handling bursts of variable size without incurring delay in message delivery. In a production network, it is unlikely that a single phone would need to receive large bursts. If the number of recipient phones corresponds to the size of message burst sent by the IM client, we will observe a constant delay across burst sizes, which will be close to the minimum measured delay – between 2 and 4 seconds.

In the second experiment we evaluate the impact of SMQueue load on the end to end delay during message

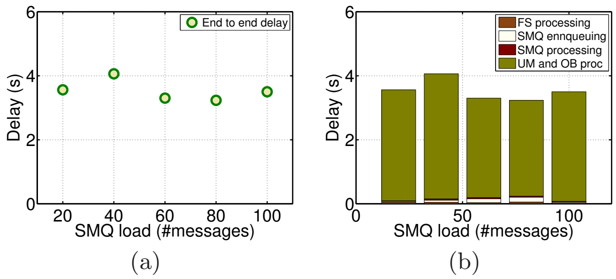


Figure 15: Impact of SMQueue load on message delivery delay from IM to a Kwiizya user: (a) end to end delay and (b) breakdown of delay components.

bursts. To do so, we send bursts of messages to a mix of associated and non-registered users. To generate load in SMQueue, we transmit an increasing number of messages to a non-registered user, starting at 20 messages, and add 20 messages at each of five iterations. At each SMQueue load level we also send a burst of three messages – one to each of the three phones associated with Kwiizya. We measure the end to end delay and delay components for delivery of these three messages. Figure 15 presents our results. In 15(a) we plot the average end to end delay for the three deliverable messages sent at each iteration, as a function of SMQueue load. The delay does not increase with the increase of SMQueue load up to a hundred messages, which demonstrates Kwiizya's capability to deliver bursts of messages without negative impact from the number of enqueued messages in SMQueue. In Figure 15(b) we plot the delay components averaged over the three deliverable messages as a function of the SMQueue load. As we can see, the delay caused by the Um interface is still the largest delay component, while the one introduced by SMQueue is negligible.

6.2 Kwiizya field usage

We now present results from in-situ usage of our Kwiizya deployment in Macha from a period of two weeks in July 2012. We begin by describing our traffic collection system. We then evaluate call quality and compare with results from our controlled experiments. We note that the backhaul Wi-Fi link in our deployment in Macha carries live Internet traffic and thus there may be variability in results due to competing traffic. The impact of this background traffic on call quality was evaluated in our previous work [5].

6.2.1 Kwiizya monitoring

As noted in section 5, our deployment includes two base stations – water tower (WT), which runs OpenBTS, FreeSwitch, SMQueue and Sipauthserve; and LITA (LT), which runs only OpenBTS and connects to WT to use other services. To capture all system traffic, we installed three monitoring points and run tcpdump at each point to capture SIP and RTP traffic:

- *lo@*WT – the loopback interface at the water tower base station that captures all internal communication in WT between FreeSwitch, SMQueue and Sipauthserve. This monitoring point allows evaluation of calls where either or both the MCO and the MCT are in the vicinity of WT.
- *eth@*WT – the Ethernet interface at the water tower base station that connects to the Wi-Fi link from the water tower to LITA and captures all communication between WT and LT. This includes all SIP and RTP traffic related to calls where either one or both communicating parties are associated with LITA.
- *eth@*LT – the Ethernet interface at the LITA base station that connects to the Wi-Fi link from the water tower to LITA. This monitoring point captures the same traffic as *eth@*WT, however with different timing of packets. This allows us to assess timing related aspects of the system.

6.2.2 Voice call quality

Delay, Jitter and Packet Loss. Delay, jitter and packet loss are three characteristics of a VoIP session that are critical to voice quality. ITU recommendation G.114 mandates that tolerable one way delay is up to 150 ms [2]. The theoretical delay minimum that a system can provide is dependent on the used codec. Kwiizya uses GSM 6.10, for which the minimum delay is 20 ms. We evaluate these characteristics in our system by analyzing 52 VoIP sessions from Kwiizya users in Macha. Figure 16 presents our results. For each VoIP session, Figures 16(a) and 16(b) plot the average and standard deviation of delay and jitter. A single point shows the average delay or jitter and standard deviation across all packets within that VoIP session. Both delay and jitter are well below the tolerated thresholds for VoIP. At the same time, the average delay is close to 20 ms over all VoIP sessions. Furthermore, delay and jitter do not vary much over a single VoIP session as indicated by the standard deviation bars, which shows that Kwiizya has stable performance throughout a call. Finally, Figure 16(c) plots packet loss over the 52 VoIP sessions. Only three of all sessions suffered non-zero packet loss; however, these three were all less than 0.5%, which is within the limit for satisfactory call quality.

Mean Opinion Score. Mean Opinion Score (MOS) is a metric that describes the call quality as perceived by the communicating parties. The maximum MOS that a system can provide is dependent on the voice codec. We evaluate the MOS achieved by Kwiizya by utilizing the E-model [3]. This model takes into account the codec type as well as experienced packet loss during a call and outputs the MOS. According to the E-model, MOS is calculated as follows:

$$MOS = 1 + R.0,035 + R.(100 - R).(R - 60)).7.10^{-6} \quad (1)$$

where R is the *rating factor*, calculated as a function of the *effective equipment impairment factor* Ie_{eff}:

$$R = 93.2 - Ie_{\text{eff}} \quad (2)$$

The *effective equipment impairment factor* is packet loss dependent and can be found as follows:

$$Ie_{\text{eff}} = Ie + (95 - Ie).\frac{ppl}{ppl + bpl} \quad (3)$$

where Ie is the *equipment impairment factor* taken for zero packet loss; bpl is the *packet loss robustness factor* and ppl is the *packet loss probability.* Ie and bpl are given for different codecs in a recommendation by ITU [1]. For a single VoIP session consisting of two RTP streams (one forward and one

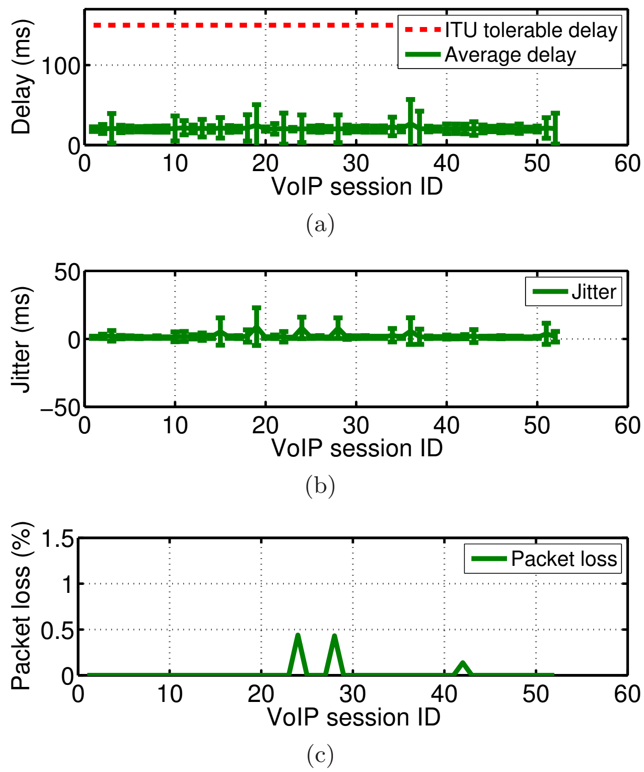


Figure 16: Field call (a) average delay; (b) average jitter and (c) packet loss.

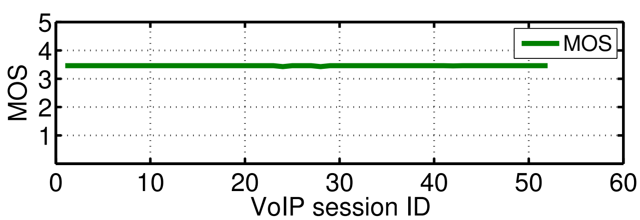


Figure 17: Mean Opinion Score.

reverse), the *ppl* value is calculated as follows:

$$totLoss = loss_{fwd} + loss_{rvs}$$
$$totSent = sent_{fwd} + sent_{rvs}$$
$$ppl = \frac{totLoss}{totSent} \quad (4)$$

FreeSwitch uses the GSM FR (6.10) codec, for which the Ie and bpl values are 26 and 43, respectively [1]. Given these, we can calculate that the maximum expected MOS provided by GSM FR (6.10) is **3.46** (effectively this is the MOS for $ppl = 0$).

Figure 17 presents our results for MOS for the 52 VoIP sessions. On the x-axis we have session ID, while on the y-axis we have MOS. The minimum measured MOS is 3.43 and the maximum (received by 49 of the 52 sessions) is 3.46 – equal to the maximum provided by the system.

Controlled vs real call. We compare the performance of a call conducted in our Macha testbed and one from a user in the network. Both calls are characterized by the same packet size and inter-packet timing of RTP packets

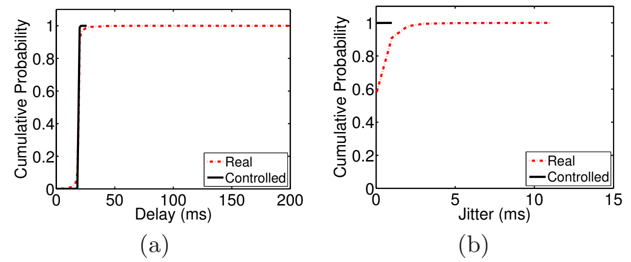


Figure 18: Controlled vs. actual user call: CDF of per packet (a) delay and (b) jitter.

in the media streams. There are two major differences between the Macha testbed and the actual deployment. First, the testbed uses a wired backhaul, whereas the actual deployment uses a long distance Wi-Fi link for inter-base station communication. The second difference is the distance between the users and the base stations to which they are connected; while in the testbed our GSM modems are only about 40m away from the base station, in the actual deployment phones can be anywhere in the range of a base station. Probabilistically, they are further than 40m since the transmission range is approximately 3km.

We present our comparison results in Figure 18. 18(a) and 18(b) plot CDFs of per-packet delay and jitter, respectively. The black solid line in both graphs presents results from our controlled call while the red dotted line presents results from a representative call from the actual deployment. We can clearly see the impact of the wireless link and the longer radio link to users' phones on the per-packet delay and jitter. While in our controlled call we experience a maximum delay and jitter of 26ms and 1ms, the actual call experiences slightly higher values. Nevertheless, more than 99% of the packets in the actual call experienced delay less than 30ms and jitter less than 3ms, which indicates that utilizing a long distance wireless backhaul link and realistic distance from users to base stations, Kwiizya can provide for delay and jitter well below the thresholds that threaten performance.

6.2.3 *Text messaging*

During our two week evaluation period, we observed only three text messages exchanged between Kwiizya users. From our conversations and interviews with cellphone users in Macha and the surrounding villages, we learned that residents typically use SMS more frequently in production cellular systems due to the lower cost of SMS in comparison with a voice call. When voice calls are more affordable, people prefer to call instead of text. This is in line with the oral communication culture within these communities, as well as high illiteracy rates. From our initial analysis of Kwiizya traffic, we observe the tendency of users to place voice calls instead of sending SMS messages because voice calls are free. However, it remains to be seen whether this observation would continue to hold once Kwiizya is opened to the general community.

7. RELATED WORK

The impact of cellphone technology on residents of developing countries has been widely studied [4, 9]. Examples from the literature show that cellphones have changed the way people learn and exchange knowledge, get access to health care and handle local government activities. There is increasing effort to develop applications that use plain text messaging and voice to leverage existing feature phones. These applications can be largely divided into those that use voice and those that use text messaging. In [23] for instance, the authors deploy a social network based on voice forums for farmers to exchange knowledge about crops and crop prices. [19] proposes a method for message exchange where messages are encoded as a sequence of missed call durations. Numerous applications use text messaging as a platform. Use cases include update of remote databases through SMS [16], attendance tracking [25], web search [8] and health care [6, 10, 15, 21].

The drawback of these solutions is that they all assume existence of an underlying cellphone network. However, ITU statistics show that 48% of the rural population in sub-Saharan Africa is still disconnected; this constitutes a large fraction of a population that benefits most from the outlined applications.

A few projects discuss alternative cellular network solutions for remote areas [12, 18]. Heimerl and Brewer were the first to propose the use of a PC and a SDR for cellphone coverage [12]. The paper describes an idea for providing intermittent cellular access to under-serviced areas, where the design focus is on minimizing the energy consumption for running a rural base station. Mpala et al. study the applicability of an OpenBTS based system in rural areas [18]. The paper describes a show case deployment of an OpenBTS and Asterisk-based cellular network with a limited range. These papers provide insight on design of such systems and discussion of obstacles to implementation; what they lack is holistic system design and large-scale evaluation of feasibility from a system point of view.

8. DISCUSSION AND CONCLUSION

The introduction of software-defined radios and software that converts GSM signals to voice over IP allows design of low-cost local cellular networks, which can notably improve communication in remote communities. We leverage these technologies and deploy the first large-scale prototype of such a network, Kwiizya, in the remote community of Macha in Zambia. While Wi-Fi is available in the community, access to the Wi-Fi service and Wi-Fi enabled user equipment is expensive. As a result, the majority of the people in the community only have access to feature cellphones. Kwiizya leverages unmodified cellphones to provide voice and SMS services; this capability is essential to covering large populations.

Kwiizya can scale to larger deployments through multiple options. It can use long-distance wireless links to physically connect communities that are a few kilometers apart. In cases where Internet is available, Kwiizya can use a globally accessible Private Branch Exchange server to connect individual installations through the Internet without the need of a physical connection between these installations.

Kwiizya can also interface with global services such as GoogleVoice, Skype or commercial operators, which allows Kwiizya users to call and text with other users who are outside the local network. We explored a configuration that uses GoogleVoice for outbound calls and text messaging; however, frequent changes in the GoogleVoice API as well as the inability to hide caller ID stopped us from opening outbound services to our users in this deployment. We plan to continue development of this option in the near future.

A reliable power supply is a major fraction of both capital and operating expenses in remote cellular deployments. Many remote deployments typically operate off the power grid, which requires alternative power sources such as diesel generators or renewable alternatives. 80% of the power consumption of a commercial cellphone network is induced by the base stations [17]; this constitutes a major fraction of the operation cost. This expense is further increased in the case of remote deployments due to the need for transportation of diesel or maintenance of renewable power sources. While this paper is not concerned with thorough evaluation of power consumption, we note that Kwiizya has significant advantages in power consumption in comparison with a commercial system. While a RangeNetworks SNAP unit such as the ones we use in Macha draws a maximum of 35W[8], a typical commercial-grade cellular base station[9] consumes 1.3kW. Thus, Kwiizya has great potential to reduce the operating expenses associated with power supply for small-scale local deployments.

While in this paper we focus on technology, there are several economic and regulatory factors beyond the scope of our work that influence the deployment of alternative cellular solutions in under-provisioned areas. Economic factors concern availability of financial resources to provision power, Internet access and equipment (software and hardware), while regulatory factors are largely related to licensing. Our partnership with LinkNet in Macha has helped us address economic aspects of Internet access and power availability. As opposed to a commercial-grade cellular system that uses licensed and costly software, Kwiizya relies entirely on free, open-source software. This, coupled with lower-cost hardware, reduces the cost for a singe base station by five to ten times in comparison with a commercial-grade counterpart. Licensing for experimental purposes is widely unregulated in sub-Saharan Africa. In Zambia, there is a national regulatory organization that governs the distribution of spectrum resources; however, there is no policy for granting experimental licenses [18]. Furthermore, pricing of commercial licenses is oblivious to the potential return of investment. We argue that lower pricing or subsidizing commercial licenses for economically unattractive areas such as rural areas would encourage entrepreneurs to seek alternative technologies and deploy in such areas. In this context, while Kwiizya has great technological potential to provide low-cost cellular infrastructure, the full potential of the system is yet to be realized. This realization largely depends on multi-faceted economic analysis of alternative solutions for cellphone access.

Deployments in remote areas require systems independent from factors such as power quality and availability, weather and network integrity. We have identified a few aspects of Kwiizya that need to be improved to make the system even more suitable for deployment in any remote community. First, a transition to solar power would facilitate deployment independent of the power grid and provide high quality power. A follow up evaluation would then help realize Kwiizya's potential to operate in the face of intermittent power availability. Second, it is very important to weather-

[8]`http://www.rangenetworks.com/store/snap-network`

[9]We compare with a Siemens BS-240 that supports 24 simultaneous calls and has a 40W output power amplifier.

proof a system that is installed in the field. For example, one of our base stations in Macha was damaged by lightning; we have learned first hand the importance of good insulation and lightning surge protectors. Lastly, to handle network integrity problems and provide continuous service, Kwiizya must be self-organizing, meaning a base station needs to sense whether access to central services is available and, if not, switch to another central server or fall back into self-contained mode.

Kwiizya is the first full scale deployment of an alternative, affordable cellular communications architecture for rural areas that lack cellular coverage. Through extensive evaluation, we demonstrated Kwiizya's capability to provide high quality services even through shared backhaul. Kwiizya reduces the capital expense by using free open-source software, SDR-based hardware and universal IP backbone. Kwiizya also reduces operation expenses by incurring much lower power consumption in comparison with a commercial cellular network. Kwiizya provides an efficient platform for SMS-based applications. Part of our ongoing work focuses on the design of such applications after careful consideration of specific needs in the community. We plan to continue to work with our partners within the Macha community to extend deployment of our solution to surrounding areas that lack cellular services, to both residential and public service areas, such as rural health posts, that are currently completely disconnected. Through longitudinal studies, we hope to provide further insights on the adoption and impact of our deployment on the local community.

9. ACKNOWLEDGEMENTS

This work was funded in part through NSF Network Science and Engineering (NetSE) Award CNS-1064821 and through a grant from the Bill and Melinda Gates Foundation. We are very thankful to our sponsors for enabling this work. We are also thankful to our partners from Macha: Gertjan van Stam, Consider and Pharren Mudenda, Austin Sinzala and Acent Milimo. We would also like to thank RangeNetworks for their support, Veljko Pejovic and David Kotz for their valuable feedback, and Kate Milosavljevic for her help with the interviews.

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