VillageCell: Cost Effective Cellular Connectivity in Rural Areas

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ABSTRACT

Mobile telephony brings clear economic and social benefits to its users. As handsets have become more affordable, ownership has reached staggering numbers, even in the most remote areas of the world. However, network coverage is often lacking in low population densities and low income rural areas of the developing world, where big telecoms often defer from deploying expensive infrastructure. To solve this coverage gap, we propose VillageCell, a low-cost alternative to high-end cell phone networks. VillageCell relies on software defined radios and open-source solutions to provide free local and cheap long-distance communication for remote regions. Our architecture is simple and easy to deploy, yet robust and requires no modification to GSM handsets. Through measuring the call quality metrics and the system capacity under a realistic rural-area network load, we show that VillageCell is indeed an attractive solution for rural area voice connectivity.

Categories and Subject Descriptors

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

General Terms

Design, Experimentation, Human Factors

Keywords

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

1. INTRODUCTION

Voice communication is extremely important in rural areas of the developing world. The lack of transportation infrastructure, high illiteracy levels, and migrant labor are some of the characteristics of rural areas that emphasize the need for real-time voice communication. In addition, even more than in the developed world, voice communication in the developing world is a strong enabler of political freedom [18], economic growth [3] and efficient health care [24].

The unique disposition of African villages, characterized by low population density and low-income communities, along with the specific cultural context represented by a mix of languages and ethnicities, and the chiefdom-based political structure, impact both the need for, and the adoption of voice communication. To better understand the way rural Africans indigenize voice communication tools, we conducted a survey of two villages in South Africa and Zambia. The specific villages were chosen because they are connected to the Internet through local wireless networks. We investigated the usage of Voice-over-IP (VoIP) applications, such as gTalk and Skype, in these villages. These applications enable virtually cost-free PC-to-PC communication. Our findings show that, despite having global connectivity, rural dwellers prefer voice for local, intra-village, communication. Unfortunately, while VoIP communication experiences few problems in the developed world where high quality connectivity is available, rural wireless networks cannot successfully carry VoIP calls, even within a single village, due to technical obstacles that we describe in section 2.

Cellphones are another option for voice communication. Cellphones are robust low power devices with a very simple and intuitive user interface. This makes them highly suitable for rural populations in the developing world where energy and infrastructure shortages, as well as language and computer illiteracy, are common problems. Indeed, cellphone penetration has skyrocketed in the last decade. In particular, the last few years saw an unprecedented increase in the number of mobile handsets shipped to the developing world. The percentage of the population who owns a cellphone in the developing world jumped from 23% to 68% in just the last five years [2].

Large telecom operators, however, remain reluctant to deploy cellular infrastructure in remote areas [8]. Rural areas in both the developed and developing world typically have either limited cellular connectivity or no connectivity at all. Currently, deployment of cellular networks is complex and requires installation of Base Transceiver Stations (BTS) and supporting infrastructure. The installation cost is high, and it remains difficult for operators to establish a profitable network in areas with low income and population density. In addition, with seasonal revenues coming from subsistence agriculture, rural users often buy prepaid airtime non-uniformly throughout the year, thus leaving telecoms without a con-

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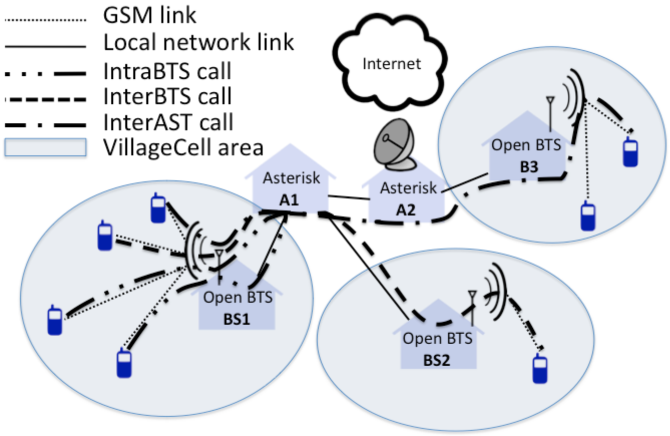

Figure 1: VillageCell network architecture. OpenBTS provides local coverage, while Asterisk nodes support call management and routing. The expected number of users, their spatial layout, and the local network traffic load are taken into account for OpenBTS and Asterisk interconnection and placement.

stant funding source [12, 9]. Compared to VoIP, cellphone calls can be prohibitively expensive.

In this paper, we propose a cost effective architecture, dubbed VillageCell, for a GSM cellular network that operates in conjunction with a local rural-area network that serves as a backbone[1]. The solution uses a Software Defined Radio (SDR) controlled by a software implementation of the GSM protocol stack, called OpenBTS[2]. OpenBTS uses SDR for transmitting and receiving in the GSM bands and serves as a local cellphone base station. To extend coverage, multiple BTSs are connected through a local wireless network and calls are managed and routed via Private Branch Exchange (PBX) servers implemented in *Asterisk*[3]. Figure 1 illustrates an example of the proposed VillageCell network architecture where cellphones, OpenBTS and Asterisk entities interconnect to offer widespread cellular connectivity. We describe in detail the different types of calls illustrated in the figure in section 5.

VillageCell integrates GSM with VoIP telephony in a cost effective manner: OpenBTS provides core cellular services for a fraction of the cost of a commercial base station, while a local wireless network brings free VoIP-based communication to cellphone users. In this way, VillageCell delivers free local cellphone communication; it supports short messaging service (SMS), does not require any modification on the end-user devices and works with existing SIM cards, all key requirements for successful adoption in a developing region.

VillageCell is specifically tailored to the spatial layout of villages in the developing world and the lifestyle of the local population. These villages typically consist of clusters of homes spread over a large area, and thus are served efficiently with multiple short-range low-power base stations. Villages often feature a single community center where schools, hospitals and markets are located. Consequently, predictable daily migration patterns can be harnessed for deployment planning or energy duty cycling.

While a single instance of OpenBTS has been proposed for rural communications before [11], to the best of our knowledge, VillageCell is the first system that provides coverage to whole villages. From that aspect, we are faced with a number of challenges. Our first challenge is related to placement and interconnection of multiple BTSs and PBX servers. VillageCell leverages any existing local wireless network. Thus, the location of BTS and PBX within the network can impact both legacy traffic as well as voice communication. The second challenge stems from the relative infancy of OpenBTS. The lack of comprehensive evaluation of OpenBTS performance as the traffic load on the wireless network and the number of users in the system change leaves us without any information on the VillageCell call quality and the system capacity. Finally, VoIP traffic is sensitive to packet delay and delivery reliability. In our previous work, we observed high variability of traffic load in a rural area network in Zambia [13]. Whether VillageCell can perform successfully in such a network is an important question we seek to answer.

To address the above challenges we construct a sample instance of VillageCell and evaluate its performance. We mix VillageCell traffic with a real-world wireless network trace gathered in Macha, Zambia to account for realistic conditions that inter-PBX communication faces in rural areas. The key results from our analysis, such as the call setup time, packet loss, delivery delay and jitter, demonstrate that VillageCell is indeed a viable and attractive solution for local rural area communication. We experiment with different BTS and PBX connection configurations and varying background traffic load. From the experimental results we derive guidelines on how to plan a VillageCell deployment. Parameters such as the number of users and the expected backhaul traffic load and its variation determine the optimality of BTS and PBX placement and interconnection.Finally, we discuss issues tightly connected with VillageCell implementation: equipment power requirements and transmission licensing.

2. VOICE COMMUNICATION IN EMERGING REGIONS

Voice-based applications have the potential to revolutionize developing regions. Well suited for areas with low literacy, voice delivers both global Internet content [15] and region specific information [20] to remote communities. The range of applications spans from micro-payment management [16] to education [25] and health care [24]. Access to information is crucial for economic growth of a region [3] as well as for political freedom [18].

While the above benefits can be observed worldwide, the way communication tools are used often varies among different regions. Local ethnographies steer the appropriation of technology according to indigenous customs [6, 12]. In our work we concentrate on sub-Saharan Africa: a region where the narrative culture emphasizes the need for voice communication, where the lack of infrastructure is pronounced and where the dispersion of population across a large geographic area makes the existing voice connectivity approaches challenging to implement.

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[1] Note: In this paper, we use the term “local network” to mean the network within a rural village or community, connected to the Internet through an Internet gateway (i.e. a satellite link, a long distance WiFi link [21, 22], etc.)

[2] http://openbts.sourceforge.net

[3] http://www.asterisk.org

Figure 2: Map of Southern Africa. Highlighted are the locations of Macha and Dwesa. Both villages are the "real rural Africa". However, Macha is located in one of the world's poorest countries – Zambia, while Dwesa, although itself very impoverished, is a part of the richest country in Africa – South Africa. The social environments of the two areas are therefore very different, as are migration patterns, crime rates and other factors.

2.1 VoIP in Macha and Dwesa

Macha, Zambia and Dwesa, South Africa are two villages that represent the "real Africa" (figure 2). They are characterized by subsistence agriculture, underdeveloped road and power infrastructure and low population income. Yet, unlike the majority of African villages, Macha and Dwesa host local wireless networks that, through a satellite gateway, bring Internet connectivity [17, 19]. To understand the way rural Africans appropriate voice-over-IP (VoIP) communication, we conducted interviews among the residents of Macha and Dwesa in July/August 2010. We interviewed a total of 37 people, age 18 to 57, 15 of them female and 22 male. We supplement the interviews with a two-week trace of all network traffic from Macha, gathered by our team in February 2010 [14, 13].

VoIP is highly popular in both villages, and 73% of interviewees use it through applications such as gTalk and Skype. Analysis of the traffic trace from Macha further supports this claim, with VoIP potentially contributing up to 26% of the traffic volume [13].

From the communication system design perspective, the locality of interactions plays a significant role in determining the most appropriate solution for a specific region [26]. Therefore, we investigated the locality of online interaction via various means of communication. With 80% of correspondents using VoIP for intra-village interaction, VoIP is the main tool for local communication. Email, on the other hand, is used for local communication by 47% of the interviewees. This is not surprising as synchronous communication provided by VoIP remains more suitable for cases where personal contact might happen often, such as when both parties live in the same area. Our findings that voice interaction is indeed highly popular in rural Africa and that it is predominantly used for local conversation, encourage further investigation of technologies that enable such communication.

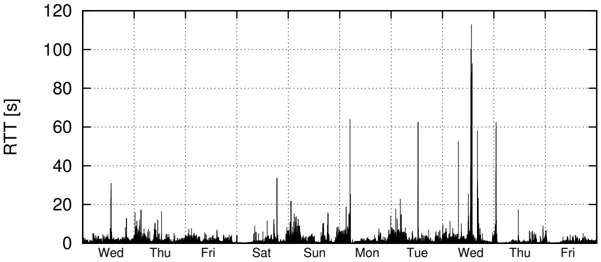

Figure 3: TCP round trip time (RTT) in Macha, Zambia over ten consecutive days. Average round-trip time measured in one minute bins. RTT is often on the order of tens of seconds, rendering voice communication practically impossible.

2.2 Technology for voice communication

Community networks in the developing world, including those in Macha and Dwesa, often consist of a single satellite Internet gateway and a wireless network that provide the connectivity to a number of end-users. In such a setting, the gateway is the bottleneck and limits the network performance. Internet-based VoIP is ill-suited for this type of a setup as voice applications such as gTalk and Skype establish a call between two nodes through a third-party Internet server[4]. In practice, this means that all VoIP communication between two persons residing in the same village has to go from the sender, over the highly congested satellite link, to the outside server, and back to the village along the same satellite link to the recipient. This makes meeting quality of service constraints exceedingly difficult, if not impossible.

To quantify the impact of limited network resources on the server-oriented VoIP communication, we measure the round trip time (RTT) of a TCP packet from a machine in Macha, Zambia to its Internet destination over the satellite link, and back the same way. Figure 3 shows that the time is often on the order of tens of seconds, rendering VoIP virtually unusable. Indeed, the fact that Skype calls are frequently dropped was the most common complaint we recorded in our interviews.

The performance of VoIP can be enhanced through either reorganization of the way VoIP traffic is handled, by keeping the traffic within the village for example, or through significant improvement of the outside Internet connection of rural villages. Cellular telephony, on the other hand, is robust to the above technical issues. In addition, cell phones are far more prevalent than PCs and laptops[5]. Mobile telephony in rural developing areas faces two major problems: the coverage is often not available in sparsely populated rural areas due to high installation and operational cost, and low, sea-

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[4] In the case of Skype, that server is called *supernode*, and represents a Skype user with very good connectivity, thus very likely outside of the rural area.

[5] In line with the global trends, we also find that 100% of interviewees in Macha and Dwesa own a cell phone, even though cellular coverage is sporadic.

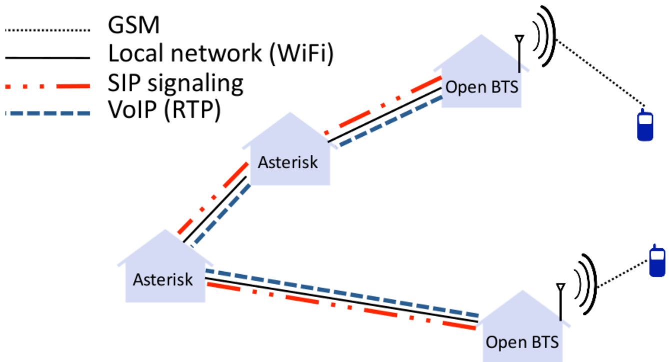

Figure 4: VillageCell protocols. On the MAC/PHY layer VillageCell relies on GSM and a local network protocol (usually WiFi). SIP signaling is used to establish a call, while the RTP protocol carries voice data (VoIP).

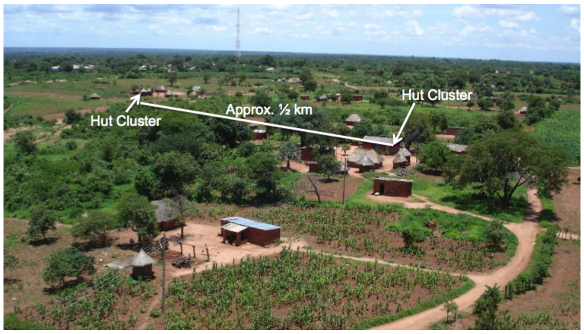

Figure 5: African village layout (Macha, Zambia). Clusters of houses are dispersed over a wide area. In Macha, the population density is 25 persons per km^2. Such a low population density, along with the low income, discourages large telecoms from deploying cellular networks in rural Africa.

sonal income makes the price of air time out of reach for many of the residents.

3. VILLAGECELL

We harness the usability and prevalence of cellphones, with the affordability of VoIP communication, and propose VillageCell. VillageCell is designed with the following goals in mind:

- develop a low-cost, easy to deploy system that can be placed among groups of homes to provide localized cellular coverage.
- provide free cellular calls within the local network while facilitating standard telephony connections to callers outside of the local network via VoIP.
- architect the necessary system component layout so that the call setup time and call quality are optimized.

In the following section we describe our system architecture in detail.

3.1 Architecture overview

VillageCell utilizes free, open-source solutions and off-the-shelf hardware to minimize the cost. Its architecture is modular and easily extensible – the VillageCell system can grow organically with the need for coverage. The main components of VillageCell are base stations and private branch exchanges.

OpenBTS is a software implementation of the complete cellular GSM protocol stack. It provides the network functionalities of *GSM registration, location updating* and *mobility management* which are, in a commercial system, distributed over multiple components such as Base Switching Centers (BSC), Mobile Switching Centers (MSC), Home Location Registers (HLR) and Visitor Location Registers (VLR). OpenBTS essentially connects wireless signal processing with the networking aspect of telephony.

OpenBTS uses SDR in order to interface with the wireless medium. SDR consists of a radio front end that transmits/receives wireless signals at the desired frequency[6] and a general purpose computer (PC) for signal samples processing. The OpenBTS software resides on both the front end and the PC.

One important functionality of OpenBTS is the interconversion of GSM and VoIP data. OpenBTS receives the GSM signals, demodulates them and converts them to VoIP packets that carry the call data (figure 4). A call is established when the signaling between the two parties is completed. This signaling is carried out by the PBX, a telephone switch system that relies on the Session Initiation Protocol (SIP) [23].

We use **Asterisk**, an open-source PBX implementation. The Asterisk PBX works on a *client-server* model where a mobile phone in a VillageCell is presented to the Asterisk server as a SIP client through the OpenBTS station, while Asterisk acts as a SIP server. Asterisk performs call routing and call monitoring for each of the connected SIP clients. An Asterisk server also maintains a database of all mobiles across the VillageCells, not only those that are directly associated with it. Finally, Asterisk allows connectivity to the public switched telephone network, and thus, integration with the global telephone system.

The VillageCell communication range depends on the transmission power, which is limited by the specific hardware used and local regulations. In addition, villages differ in their layout. Thus, a varying number and position of cell stations is needed for different geographies. In figure 5 we show an example of a typical sub-Saharan village layout from Macha, Zambia. The houses are dispersed over a wide area in small clusters with family members living in close proximity. We envision approximately one VillageCell per cluster, dependent on the distance between such clusters.

VillageCell components can be interconnected in multiple configurations; one Asterisk server can be common to many OpenBTS cells. Alternatively a single cell can also have a dedicated Asterisk server. In addition, the backhaul wireless network can carry varying quantities of non-VoIP traffic. In Section 5 we experimentally investigate the impact of the component layout on the call quality and the system capacity.

Connection between VillageCell base stations and PBX servers, as well as among the PBX servers themselves, can be realized with any standard IP-based technology: WiFi,

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[6] GSM bands are located at 850MHz, 900MHz, 1800MHz or 1900MHz.

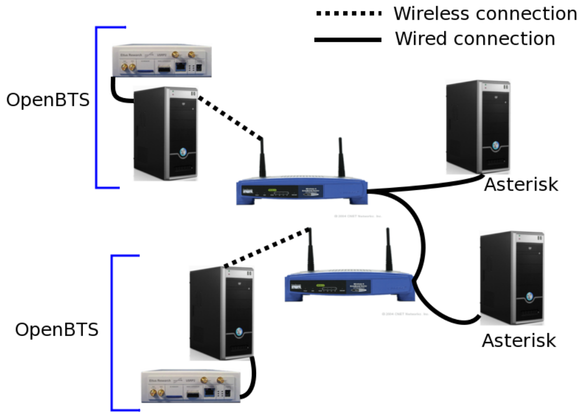

Figure 6: Experimental VillageCell setup. Shown is a configuration with two OpenBTS stations (each is composed of a USRP2 and a PC) and two Asterisk servers. The wireless routers ensure that the BTSs are connected via non-interfering WiFi channels. The rest of the configuration is connected via Ethernet.

WiMax, local Ethernet, 802.22. Local wireless (often WiFi-based) networks have been deployed in many isolated communities, such as Macha and Dwesa. If such a network exists, VillageCell can utilize it for call transfer. Within the underlying network an OpenBTS or an Asterisk server appears as just another node in the network.

4. VILLAGECELL IMPLEMENTATION

We implement a prototype of VillageCell in a lab setting using readily available hardware components. Universal Software Radio Peripheral 2 (USRP2)[7] is a commercial SDR platform that natively supports OpenBTS software. We use a USRP2 with a general purpose PC for a VillageCell base station. The USRP2 platform hosts a powerful processing circuit (FPGA) for high bandwidth communication and a transceiver capable of operating in GSM bands. In our setup we use the 900MHz band, as there are no interfering telecom carriers in that band. We do not amplify the USRP2 signal output, thus restricting the cellular coverage to a single indoor lab.

For PBX, we use commodity PCs running Linux and the Asterisk software. Since Asterisk does not need a dedicated PC, it could be installed on the same machine on which OpenBTS is running. However, in order to isolate different parts of the system, we install Asterisk servers as separate entities. Connection among the components is established through two Linksys WiFi routers as per figure 6. This setup represents a scaled down version of VillageCell that would be deployed in the real-world and helps us isolate the impact of individual factors, such as network layout, wireless interference, and background traffic, on the performance.

We test our VillageCell implementation with three phone models: Nokia 3510 (from year 2002), Nokia 5300 Express Music (2006), and HTC Dream Android phone (2009). We also test the system with a range of SIM cards, with different memory sizes and belonging to different operators from both the developing and developed world, such as AT&T (USA), MTN (South Africa), Vodafone, Airtel and BSNL (India). Since we found no difference in the performance as we change the phone models and the SIM cards, we do not explicitly note these characteristics when reporting the experimental results.

5. EXPERIMENTAL EVALUATION

We envision the VillageCell system on top of an existing rural area network. Thus, VillageCell voice traffic has to contend with other traffic for network resources. In this section we evaluate the capacity of the VillageCell system and the call quality in a realistic rural area network setup. Real-time voice communication has stringent packet delivery and delay requirements. While our low-cost implementation of a local cell phone architecture is not intended to compete with expensive commercial telecom equipment, VillageCell has to perform well enough so that quality local phone calls can be established.

5.1 Call scenarios

Three different scenarios of a VillageCell phone call can exist depending on the relationship between the call origin/destination and the architecture layout. We show these scenarios in figure 1 and briefly describe them here:

- *Intra VillageCell Call/Intra Asterisk Call (IntraBTS):* The source and destination mobiles are registered as SIP clients under the same Asterisk server A1 and are both connected to the same OpenBTS station BS1. When a call request is made, BS1 determines the existence of the destination mobile by querying the Asterisk server A1 through *SIP Invite* signaling [23]. If a match is found then a communication channel is established between the station BS1 and the server A1 as *BS1 - A1 - BS1* and the call is connected.
- *Inter VillageCell/Intra Asterisk Call (InterBTS):* Here the source and destination mobiles are registered as SIP clients under the same Asterisk server A1 but under different OpenBTS stations. BS1 corresponding to the caller mobile contacts its controlling Asterisk server A1 and verifies the existence of the called mobile in a different VillageCell (with station BS2) through *SIP Invite* signaling. If a match is found then a communication channel is established between the two stations as *BS1 - A1 - BS2* and the call is made.
- *Inter VillageCell/Inter Asterisk Call (InterAST):* In this case, each of the two communicating mobiles is registered as a SIP client with different Asterisk servers. OpenBTS station BS1 corresponding to the caller mobile contacts its controlling Asterisk server A1 and queries for the existence of the called mobile. The Asterisk server A1 in turn contacts Asterisk server A2 for the destination mobile's verification using *SIP Invite* signaling. If a match is found then a communication channel is established between the two stations as *BS1 - A1 - A2 - BS3* and the call is made.

Intuitively, the call scenario depends on the caller and callee position in the area served by VillageCell. However, with careful planning we can lay out the VillageCell components so that desirable scenarios occur more frequently than the others.

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[7] http://www.ettus.com

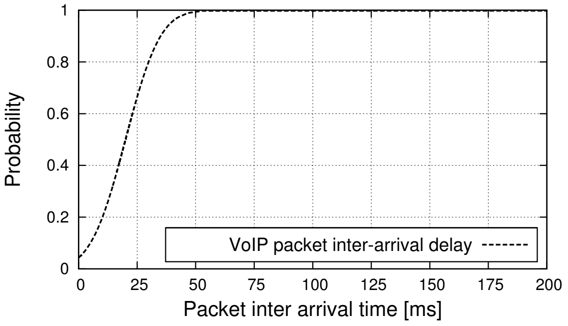

Figure 7: CDF of interarrival delay.

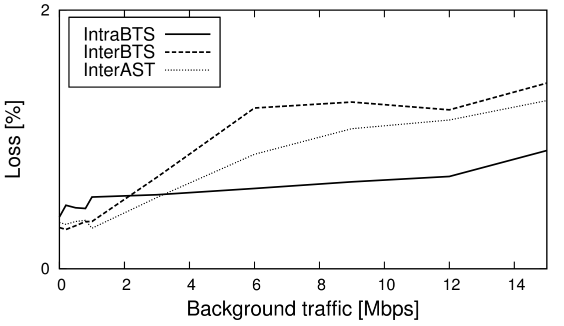

Figure 8: Packet loss with varying level of background traffic.

5.2 VillageCell call quality

To quantify the performance of our proposed architecture, we measure call setup time, maximum VoIP latency, delay jitter and VoIP packet loss for voice calls. We evaluate these parameters for each of the three call scenarios mentioned above. In a production network, the underlying wireless network will carry traffic in addition to VillageCell VoIP. To test the system under varying background load, we run a constant stream of UDP traffic with *iperf*[8] between the PBX servers, as well as between the PBX servers and BTSs, and vary the UDP traffic load between experiments. In each of the experiment runs we conduct a three minute long call, and for each of the data points, we average over five runs.

We measure the call setup delay as the time duration between the call initiation (SIP Invite signal) and call ringing notification (SIP 180 Ringing signal), both on the calling OpenBTS. In our experiments we observe call setup delay in the range of 1.5-2.0 seconds, which is an acceptable value. The default GSM voice encoding in our experiment is G.711 μ-law. This codec transmits packets every 20ms. At the receiver, we measure the interarrival time between consecutive packets in a voice stream. In figure 7 we provide the cumulative distribution of interarrival delay for the case of InterAST scenario with 1Mbps of UDP background traffic. As observed from the figure, 85% of the VoIP packets have interarrival time of less than 25ms, with 95% having interarrival time of less than 40ms. The figure demonstrates that the VillageCell system is able to process and forward the packets while introducing little disturbance in the flow.

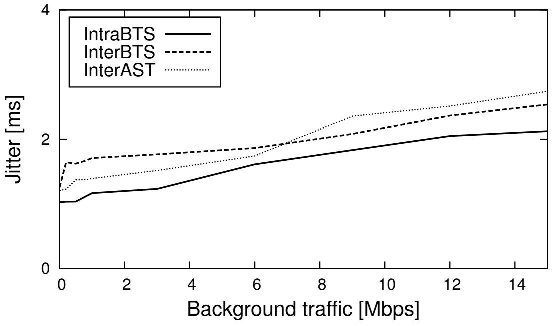

Figure 9: Delay jitter with varying level of background traffic.

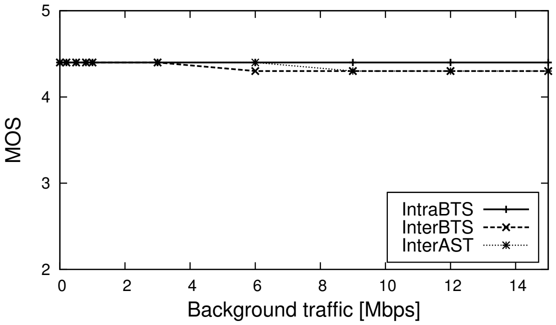

Figure 10: Mean opinion score (MOS) with varying level of background traffic.

In figure 8 we show end-to-end VoIP packet loss in the three scenarios. We push the UDP background traffic as high as 15Mbps; beyond 15Mbps network saturation occurs. The VoIP loss grows linearly with the background traffic and reaches the maximum at 15Mbps, with 1.4% packet loss. The loss tolerance of the G.711 codec is relatively high, and as long as the packet loss stays below 10%, speech communication is possible. Our results show that packet loss does not limit VillageCell usability in these tests.

VoIP packets are sent at uniform 20ms intervals; however jitter in their inter-arrival time can impact call quality. We measure the jitter in all three test cases and show the results in figure 9. We observe that the jitter increases linearly with the amount of background traffic. To cope with high jitter, VoIP applications often implement receiver-side buffers that store packets for some time (usually less than 100ms) and then send them to the decoder in regular intervals. The buffering, however, increases end-to-end call delay. In our setup, the maximum jitter is always below 3ms, thus even a short amount of buffering suffices.

Voice call quality is often expressed in mean opinion score (MOS) and ranges from perfect (5) to impossible to communicate (1), where any score higher than 3 is considered acceptable. E-model [1] converts packet loss and voice codec information into MOS[9]. In figure 10, we show MOS values for each scenario with increasing background traffic. In all the cases call quality remains above 4, i.e. very good.

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[8] http://iperf.sourceforge.net

[9] We keep the default GSM codec G.711 μ-law.

	IntraBTS	InterBTS	InterAST
Trace from Macha, Zambia	0.69%	0.82%	0.88%
iperf-generated TCP	1.00%	1.32%	1.81%

Table 1: Packet loss in a VillageCell system with varying background traffic types.

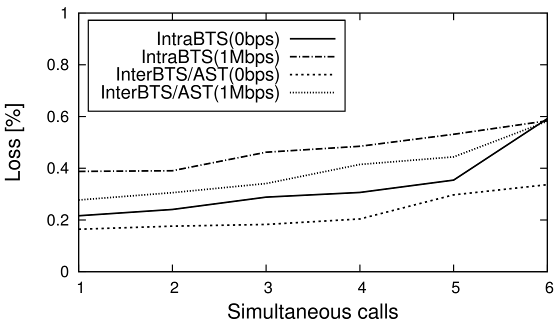

Figure 11: VillageCell performance with varying number of simultaneous calls.

5.3 Realistic load experiments

Next we investigate VillageCell performance when the voice traffic is mixed with a traffic trace gathered from a wireless network in Macha, Zambia. This trace contains a mix of Internet protocols as the network is used for web browsing, email and non-VillageCell VoIP services, among other purposes. The full analysis of the trace content is available in [14]. In our testbed we replay a randomly selected, ten minute snippet of traffic from Macha. Similar to the UDP background traffic, we measure the packet loss that a single call experiences in each of the three configurations. For comparison, we run a separate set of experiments with iperf-generated TCP traffic as the background traffic and compare the results.

Table 1 summarizes the packet loss results from the experiment with the three VillageCell scenarios and two different background traffic types. The results are consistent with the earlier case of UDP background traffic. The packet loss remains below 2%, and higher loss is experienced in the InterBTS and InterAST scenarios than in the IntraBTS scenario. This is consistent with the behavior observed under high UDP background traffic. Interestingly, iperf-TCP background traffic results in more losses than the real-world traffic from Zambia. The reason stems from the fact that iperf boosts the TCP throughput up to the limit imposed by the network conditions, which in the best case allow up to 54Mbps. The traffic in Zambia, on the other hand, is more strictly limited by the satellite gateway capacity, which is only 1Mbps at maximum.

5.4 VillageCell system capacity

We evaluate the capacity of VillageCell when it comes to multiple simultaneous calls. In our VillageCell prototype we establish a call and incrementally add more calls, up to a maximum of six calls. Once all the calls have begun, we measure the packet loss rate in each call and calculate the average value. All calls are composed of one physical phone as a receiver and one soft-phone as a caller, due to the number of devices we have at our disposal.

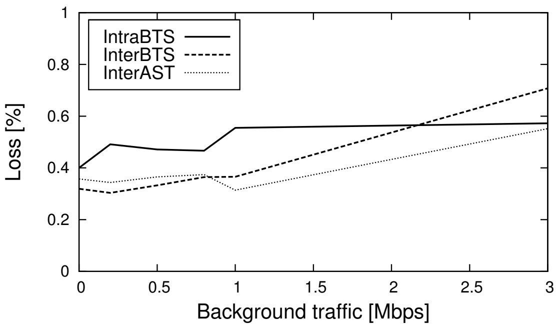

Figure 12: Packet loss under light background load.

In figure 11 we present the loss error rate for two types of configurations[10] as the number of simultaneous calls increases. We show the results with both no background UDP traffic and with 1Mbps constant UDP traffic. In all four cases call quality experiences only a minor change in packet error rate (less than 0.3% increase) as we activate all six calls. While it is promising that we observe very little impact of the number of simultaneous calls on the call quality, in the future we plan to obtain more handsets and identify the true capacity limit of VillageCell.

5.5 Impact of VillageCell layout

The experimental results from the previous sections demonstrate that VillageCell provides high quality voice communication under various network conditions. In addition, to the extent that we could test it, the VillageCell system scales well with the number of concurrent calls in the system. However, differences in the call quality can be noted among the three VillageCell scenarios: InterBTS, IntraBTS, and InterAST setup. We analyze the three configurations with respect to the packet loss rate, delivery jitter and the number of supported calls.

First, we concentrate on packet loss rate with varying levels of background UDP traffic. In figure 8 we observed that the IntraBTS configuration results in lower average packet loss rate for all but low network loads. We enlarge the leftmost part of the graph in figure 12. We observe that at less than 2-3Mbps of background traffic, both alternatives (InterBTS and InterAST) perform better than IntraBTS. The explanation stems from the distribution of losses. In the IntraBTS case, since both parties are associated with the same BTS, the same call traverses a single wireless link twice, from the BTS to the Asterisk server and back to the same BTS. Thus, the flow self-interference results in some dropped packets. This does not happen in the other two cases, InterBTS and InterAST, as the flow never traverses the same link twice, nor two links in the same interference domain; the resulting loss is lower than in the IntraBTS case. When the background traffic is increased, however, the impact of uncorrelated losses on the two WiFi links (from BS1 to A1 and A1 to BS2) in the InterBTS and InterAST configuration is more pronounced than the effect of self-interference in the IntraBTS case, thus the loss is higher. Consequently, the background traffic trace from Macha, Zambia or the TCP

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[10] Since we are using one soft-phone, which runs on Asterisk, there is no difference between the IntraBTS and InterBTS cases.

	Low background traffic	High background traffic
Packet loss	InterBTS/InterAST	IntraBTS
Delay jitter	IntraBTS	IntraBTS
System scaling	InterBTS/InterAST	InterBTS/InterAST[11]

Table 2: Summary of VillageCell layout on the call performance. We show the optimal layout for each of the scenarios.

streaming (which is higher than 1Mbps), is less detrimental in the IntraBTS case, as was shown in table 1.

The packet delivery jitter (figure 9) is slightly lower in the IntraBTS case than in the other two cases. The difference is minor and can be explained with more links and PCs that have to be traversed in order to establish a call in the InterBTS and InterAST scenarios.

Finally, as shown in figure 11, higher number of simultaneous calls negatively impacts the call performance irrespective of the configuration, yet the performance of IntraBTS is worse than the performance of InterBTS/AST, regardless of the number of calls. In summary, irrespective of the number of simultaneous calls, IntraBTS calls experience more packet loss than InterBTS/AST calls as long as the background traffic remains low. We recap the findings from this section in table 2.

6. DEPLOYMENT PLANNING

Our goal in designing the VillageCell architecture is for it to be flexible and adaptable to user needs. However, another set of restrictions comes from the topology of the existing community network (if any), energy resource availability, and regulatory issues. Here we discuss VillageCell planning from all of the above aspects.

6.1 Component layout

VillageCell can be built on top of an existing community wireless network. Because VillageCell performs differently in different configurations (IntraBTS, InterBTS and InterAST), and with varying levels of background traffic (table 2) we devise guidelines for VillageCell planning:

- IntraBTS performs worse than InterBTS/AST when the background traffic is low. As a consequence, where local interaction is high, and the edge of the local network is near (where the WiFi backbone ends), rather than trying to cover a large area with one powerful BTS (IntraBTS), it is more attractive to have a few BTSs and split the load between them, as in the InterBTS architecture. Consequently, the losses will be lower, as we expect low background traffic, since there will be no aggregated traffic from nodes whose path to the gateway traverses VillageCell links.
- IntraBTS is not as sensitive to background traffic (figure 8). Thus, OpenBTS-Asterisk communication can use a congested backbone link as long as the communication remains local (IntraBTS). If we consider a community where we expect a very high level of locality of interaction, we can connect the BTS and the PBX server directly to the backbone, without the need to have a separate wireless link dedicated to that connection. This reduces the planning effort and the cost of deployment.
- InterBTS and InterAST are sensitive to high background traffic. If we have two locations where we expect a lot of mutual interaction, we should connect their BTSs to a PBX(s) with dedicated WiFi links. While this may increase the cost of deployment, it assures reliable delivery of both VoIP and existing network traffic.
- Because calls are routed through the Asterisk servers, we should keep the Asterisk servers local to the BTSs in the areas of high level of local interaction to avoid packet losses that occur in BTS - Asterisk dedicated WiFi links.

6.2 Outside connectivity

VillageCell is optimized for free local communication, though it can also connect local users to the outside world using a commercial VoIP Network. In our system, Asterisk machines on the edge of the local network can be connected to the outside world over the Internet via VoIP. The traffic going to a VoIP network is billed according to the VoIP operator's usage terms. Non-local call routing is performed as follows. When an Asterisk server at the edge of the network receives a call request to a user not present in the local network, the call request is forwarded to the database of the VoIP provider to locate the user. If the user is found in the database, the subsequent call traffic is routed via a satellite gateway over the Internet. On the other hand, when an outside user calls a user who is located within the VillageCell system, the edge Asterisk server translates between a globally accessible VoIP ID and a local VillageCell phone number. In this paper, we focus on VillageCell's operation within the local network, but we note that communication outside the network is also feasible and we plan to implement it as a part of our future work.

6.3 Energy issues

VillageCell components, such as OpenBTS stations and Asterisk servers, can be built out of commodity PCs or laptops. These devices consume on the order of hundreds of Watts or less. The radio front end, provided by USRP2, consumes only up to 13 Watts. While this implies that VillageCell needs more than an order of magnitude less power than a commercial cellphone station, unreliability of the electrical grid in rural areas still presents a major problem. In [11] Heimerl and Brewer propose powering OpenBTS base stations with wind and solar energy. This attractive alternative, however, comes with an added cost of energy harvesting equipment, which could surpass the cost of communication equipment [4]. Further investigation is needed to identify the optimal energy availability – equipment cost balance, and tackle problems of possible power shortages due to unfavorable weather conditions.

6.4 Licensing issues

Worldwide, operation on GSM frequencies requires a license. Usually, a license is granted on a national or a regional level to a large telecom. However, this does not necessarily prevent smaller players from deploying OpenBTS-based systems. In the United States, FCC grants experimental licenses for GSM bands as long as the irradiated power is less than 8W. Analysis of WiFi frequency bands showed that non-restrictive licensing contributes to increased Internet connectivity [5]. The final decision, however, is on the regulatory bodies and their assessment of local cellular coverage benefits.

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[11] For system scaling experiments we gathered results with up to 1Mbps background traffic.

7. CONCLUSION

In this paper we presented VillageCell, a low-cost localized cell phone system for rural areas. We implemented VillageCell in a lab setting and evaluated it in realistic rural-area network scenarios. Through the experiments we identified technical issues that are crucial to core functionality of the VillageCell architecture: establishing local intra- and inter-VillageCell calls. We show that call quality in our system is often very good with little packet loss, fast setup time and low delay jitter. From the variations in performance that we observed as we modified the network layout, we derived guidelines for efficient VillageCell integration into an existing rural-area wireless network.

VillageCells solves an important problem of providing localized voice connectivity. In addition, through VillageCell SMS capability, or data-over-voice solutions such as [7], our system also enables free local data service. In the future, we plan to develop applications specifically suited for VillageCell's unique affordances. Moreover, many existing applications for developing regions that experience implementation problems as local population, discouraged by the cost of cellphone communication, remains reluctant to use them, can benefit from VillageCell [20, 10].

Finally, the existence of a community WiFi network and our familiarity with the Internet usage and needs of local population present a solid foundation for our planned work on deploying a full-scale VillageCell deployment in Macha, Zambia.

8. REFERENCES

[1] *ITU-T Recommendation G.107, "'The E-Model, a computational model for use in transmission planning"*, December 1998.

[2] *ITU World Telecommunication/ICT Indicators Database*, December 2010.

[3] R. Abraham. Mobile Phones and Economic Development: Evidence from the Fishing Industry in India. In *ICTD'06*, Berkeley, CA, May 2006.

[4] G. Bernardi, P. Buneman, and M. K. Marina. Tegola Tiered Mesh Network Testbed in Rural Scotland. In *WiNS-DR '08*, San Francisco, CA, Sept. 2008.

[5] M. L. Best. A Global Survey of Spectrum License Exemptions. In *The 34th Research Conference on Communication, Information and Internet Policy (TPRC)*, Washington, DC, September 2006.

[6] M. de Bruijn, F. Nyamnjoh, and I. Brinkman, editors. *Mobile Phones: The New Talking Drums of Everyday Africa*. Langaa RPCIG, 2009.

[7] A. Dhananjay, A. Sharma, M. Paik, J. Chen, J. Li, and L. Subramanian. Data Transmission over Unknown Voice Channels. In *MobiCom'10*, Chicago, IL, September 2010.

[8] A. Dymond and S. Oestmann. The role of sector reform in achieving universal access. Technical report, ITU, 2003.

[9] R. Flickenger, C. Aichele, C. Fonda, J. Forster, I. Howard, T. Krag, and M. Zennaro. *Wireless Networking in the Developing World*. Limehouse Book Sprint Team, first edition, January 2006.

[10] A. S. Grover and E. Barnard. The Lwazi Community Communication Service: Design and Piloting of a Voice-Based Information Service. In *WWW'11*, Hyderabad, India, March 2011.

[11] K. Heimerl and E. Brewer. The Village Base Station. In *NSDR'10*, San Francisco, CA, June 2010.

[12] H. Horst and D. Miller. *The Cell Phone: an Anthropology of Communication*. Berg, 2006.

[13] D. Johnson, V. Pejovic, E. Belding, and G. van Stam. Traffic Characterization and Internet Usage in Rural Africa. In *WWW'11*, Hyderabad, India, March 2011.

[14] D. L. Johnson, E. M. Belding, K. Almeroth, and G. van Stam. Internet Usage and Performance Analysis of a Rural Wireless Network in Macha, Zambia. In *NSDR'10*, San Francisco, CA, June 2010.

[15] A. Kumar, N. Rajput, D. Chakraborty, S. K. Agarwal, and A. A. Nanavati. WWTW: The World Wide Telecom Web. In *NSDR'09*, Kyoto, Japan, August 2007.

[16] D. Kumar, D. Martin, and J. O'Neill. The Times They Are A-Changin': Mobile Payments in India. In *CHI'11*, Vancouver, Canada, May 2011.

[17] K. W. Matthee, G. Mweemba, A. V. Pais, G. van Stam, and M. Rijken. Bringing Internet Connectivity to Rural Zambia using a Collaborative Approach. In *ICTD'07*, Bangalore, India, December 2007.

[18] H. V. Milner. The Digital Divide: The Role of Political Institutions in Technology Diffusion. *Comparative Political Studies*, 39:176 – 199, March 2006.

[19] N. Ndlovu, M. Thinyane, and A. Terzoli. Deployment and Extension of a Converged WiMAX/WiFi Network for Dwesa Community Area South Africa. In *Southern African Telecommunication Networks and Applications Conference*, August 2009.

[20] N. Patel, D. Chittamuru, A. Jain, P. Dave, and T. S. Parikh. Avaaj Otalo - A Field Study of an Interactive Voice Forum for Small Farmers in Rural India. In *CHI'10*, Atlanta, GA, April 2010.

[21] R. Patra, S. Nedevschi, S. Surana, A. Sheth, L. Subramanian, and E. Brewer. WILDNET: Design and Implementation of High Performance WiFi Based Long Distance Networks. In *USENIX NSDI*, Cambridge, MA, April 2007.

[22] B. Raman and K. Chebrolu. Design and Evaluation of a new MAC Protocol for Long-Distance 802.11 Mesh Networks. In *ACM MobiCom*, Cologne, Germany, August 2005.

[23] J. Rosenberg, H. Schulzrinne, and G. Camarillo. The Stream Control Transmission Protocol (SCTP) as a Transport for the Session Initiation Protocol (SIP). RFC 4168, 2005.

[24] S. Surana, R. Patra, S. Nedevschi, M. Ramos, L. Subramanian, Y. Ben-David, and E. Brewer. Beyond Pilots: Keeping Rural Wireless Networks Alive. In *NSDI'08*, San Francisco, CA, April 2008.

[25] M. Wang, R. Shen, R. Tong, F. Yang, and P. Han. Mobile Learning with Cellphones and PocketPCs. *Advances in web-based learning - ICWL 2005*, 3583/2005:332–339, 2005.

[26] M. Wittie, V. Pejovic, L. Deek, K. Almeroth, and B. Zhao. Exploiting Locality of Interest in Online Social Network. In *CoNEXT'10*, Philadelphia, PA, December 2010.