The Pilot Deployment of A Low Cost, Low Power Gateway To Extend Cellular Coverage In Developing Regions

Vijay Gabale, Ramesh Gopalakrishnan, Bhaskaran Raman
Dept. of Computer Science, IIT Bombay
Mumbai, Maharashtra, India
vijaygabale@cse.iitb.ac.in, gramesh@cse.iitb.ac.in, br@cse.iitb.ac.in

ABSTRACT

In spite of the tremendous growth in the number of cellular subscribers in the developing world, the teledensity in most of the rural areas remains very low. For instance, in India, the rural teledensity is less than 30%. There are a large number of villages which do not have cellular coverage to this day. This lack of connectivity is a major hurdle in the development of these areas. However, many such villages are only a few km away from the cellular coverage. Exploiting this, we present a low cost and low power gateway to extend the cellular coverage into the rural areas. Specifically, we develop a low cost, low power *802.15.4 gateway* which can connect a number of villages in its vicinity to the cellular backhaul. In prior work, we designed a low cost, low power 802.15.4 handset. In this work we show that, using the gateway node, the 802.15.4 handsets enable villagers to establish real-time voice calls from/to the village to/from the outside world. The handset is connected to the gateway node using an 802.15.4 mesh network. Such a network also allows villagers to make local voice calls (within the mesh network) using the 802.15.4 handsets.

We deployed the prototype of our system for a day in Ahupe village, near Mumbai, India. Using our gateway node, we successfully established several phone calls from the village to the phones in the outside world. We also established several local voice calls using the backbone mesh network, within the village. With our deployment experience, we believe that such a low cost and low power system can greatly benefit people in developing regions.

1. INTRODUCTION

In recent years, there has been tremendous growth in the number of cellular subscribers in the developing world. However, at the same time, the state of cellular penetration in rural areas is still very low. For instance, in India, out of 750 million people residing in the villages, only 250 million had cellular subscription by December 2010 [3]. About 250 thousand villages from 600 thousand do not have cellular coverage to this day. The three main reasons for such a low rural teledensity are (1) the high infrastucture cost and high power requirements of the cellular base stations (2) the low income level (order of $2-4 per day) and (3) the poor state of electricity supply (order of 6-8 hours per day). However, there are a large number of villages which do not have cellular coverage but are only a few km (or less) away from the cellular point of connectivity [4] [1]. This is largely due to the presence of cellular base stations along the national and state highways.

A specific example is a village named Ahupe, situated about 75km from Mumbai, India. Spread over 1.2 sq.km., the village is situated on the top of a mountain and the village itself does not have cellular coverage. However, there are several points on the edge of the mountain, about 0.5km away from the village, where the connectivity can be received from a number of service providers. The villagers often need to walk several hundred meters to the edge of the mountain to make a phone call and often they need to stand and wait for several hours to receive a phone call. In this respect, we seek to answer following question. *How should we extend this coverage inside the village in as low cost and power budget as possible?*

Figure 1: Deployment at Ahupe, setting up antenna for an 802.15.4 node

We, in our prior work [15] argued the use of 802.15.4 technology to build a **lo**w cost, **lo**w power, **lo**cal voice (Lo^3) com-

[1] We experienced such situations at first hand through field trips to several villages in India.

munication system inside a village. In subsequent work [13], we designed, implemented and evaluated *LiT*, a TDMA MAC protocol, to enable real-time voice streaming in multi-hop wireless mesh networks. Further in [14], we built an 802.15.4 based handset to enable a bi-directional voice using LiT MAC. In this work, we make following contributions.

• We present the design of a low cost and low power *gateway node* (§5), which enables 802.15.4 handsets inside the village to connect to the cellular network and establish voice calls with a phone in the outside world.

• We carry out a pilot deployment in Ahupe village (Fig 1) and successfully establish several voice calls from Ahupe to the phones in the outside network. We also establish several local voice calls within the village (§6).

• The cost requirement and power consumption of such a gateway node is several fold less than the current cellular technologies (§7). Thus we show that indeed it is possible to use low end platforms effectively and efficiently to enable voice telephony in rural areas.

The down sides of our system are that (1) we have to use the 802.15.4 handsets, and cannot ride on the low-cost mobile-phone market, and (2) we can provide only the hot spot coverage, and not the carpet coverage. Despite these, our deployment experience indicates that our system can be of real use to people in several scenarios.

2. RELATED WORK

In the previous section (Sec. 1), we stressed the need for a low cost and low power communication network to be applicable to the rural areas in developing world. Several communication technologies have been considered in recent time to bridge the digital connectivity gap between the rural and the urban areas. In this section, we describe pros and cons of these technologies and compare them with our approach. The comparison is based on of the following aspects: cost, power and means of connectivity to the backhaul.

We start with OpenBTS [7], an open source GSM base station, which has been proposed as a low cost and low power alternative to the cellular base stations. OpenBTS has the cost of an order of 10% of a base station (a typical base station costs about $10-100K depending on the configuration, including the set up cost) and consumes an order of 60W power. Given sufficient ground clearance (> 30m), the signal can travel upto 20km. However, this requires setting up a high rise tower which can increase the overall infrastructure cost. Also, OpenBTS requires substantial battery back up in case of power outages. OpenBTS assumes Internet connection (IP back end) to route the voice calls from the network to the outside world. Such a level of Internet penetration is quite sparse in developing regions. In comparison, as we show in Sec. 7, our gateway node is a very low cost (about $140) and low power (about 1.3 W) device. Further, it assumes a point of connectivity to the cellular base stations which is typically found in 2-3sq.km radius around a village.

Femto cell [5] is another low cost and low power cellular technology, which can be used to extend the cellular coverage for use inside a home or business unit. A Femto cell costs around 50$ [5], requires 500mW of power and can serve 2-8 active cellular phones. However, the Femto cell has a centralized, single hop architecture and the cellular coverage can be extended only up to about 100m. Like OpenBTS [7], Femto cell also requires a wired broadband connectivity to the backhaul. The state of wired broadband is quite poor across the rural areas in developing world. In comparison, within the similar cost and power budget, our gateway node can extend the coverage to several hundred meters with the use of the Lo^3 (an 802.15.4 mesh) network.

Apart from these cellular technologies, a mesh-potato box developed by VillageTelco [10] is a case of the low cost WiFi mesh network. Such a network can be used to provide local telephony services using the off-the-shelf analog phone units. In addition to local telephony, a gateway mesh-potato can be connected to the Internet and users inside the network can access the Internet applications on a laptop or desktop. Although our system and the mesh-potato network may seem to be similar in terms of functionalities (provide a local voice and a gateway facility), there are two subtle differences. Firstly, the power consumption of a Lo^3 node [15] is order of $\times$ 25 less than a mesh-potato. This makes our network robust to power failures and the network can run for several days without battery recharge. Secondly, our gateway node does not assume broadband or Internet infrastructure but presence of a cellular point of contact which can be found within 2-3km radius around a number of villages.

3. BACKGROUND

We build upon the following prior work. In our prior work [15], we argued the use of 802.15.4 technology to build a **lo**w cost, **lo**w power, **lo**cal voice (Lo^3) mesh network inside a village. In subsequent work [13], we designed, implemented and evaluated *LiT*, a multi-hop TDMA MAC, to enable real-time voice streaming in Lo^3. In particular, we showed that it is possible to implement a TDMA based multi-channel MAC on the low end 802.15.4 platforms. We evaluated various aspects of the MAC (node join latency, flow establishment latency, jitter experienced by voice calls and control overhead in the TDMA schedule dissemination) on a 19 node outdoor testbed for real-time CBR (constant-bit-rate) traffic. We used the Telosb platform and the TinyOS operating system in our implementation.

In subsequent work [14], we developed an 802.15.4 based handset to demonstrate the real-time voice communication using LiT MAC. We used Texas Instrument's C5505/15 hardware and software platform to develop the handset. We interfaced TI's IEEE 802.15.4 compliant CC2520 radio to the C5505/15 platform. This enables the handset to talk to a 802.15.4 backbone network. The C5505/15 platform can support voice sampling and playback and has a processor powerful enough to handle the speech encoding and decoding in the software. We used an open source Speex codec (with the data rate of 5.9 kbps) to encode and decode the voice samples. Using such handsets, we demonstrated the bi-directional voice call through the 802.15.4 backbone network using LiT MAC [14].

In this work, we present the design of a low cost and low power gateway node, which enables 802.15.4 handsets inside the village to connect to the cellular network and establish voice calls with the outside world.

4. SYSTEM ARCHITECTURE

In this section, we explain the overall architecture of our system, shown in Fig. 2.

The goal of the system is two-fold: (1) to set up a real-time voice call with a regular phone in the network, outside

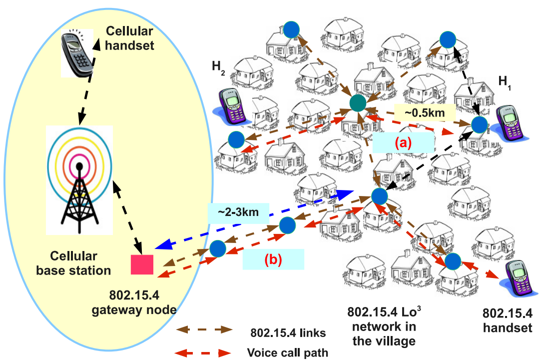

Figure 2: System architecture along with the gateway node

the village (2) to provide a real-time voice communication in the local area. The figure shows a local voice call in progress (label (a) in Fig.2) between two 802.15.4 handsets (H_1 and H_2) using the Lo^3 (an 802.15.4 mesh) network. The figure also shows a voice call (label (b)) which originates from an 802.15.4 handset, travels through the Lo^3 network, passes through the gateway node, connects to the nearby cellular base station and eventually reaches to a phone in the outside network.

In next section, we explain the design of our gateway node. In subsequent sections, we describe the pilot deployment of our system at a village site.

5. DESIGN OF THE GATEWAY NODE

In this section, we describe the hardware and software design and working of the gateway node. The main functionality of the gateway node is to route the call to/from the Lo^3 network from/to the cellular network. From the perspective of the Lo^3 network, the gateway node can be viewed as an end device which *shares* a cellular connection among multiple handsets inside the network.

5.1 Hardware interfacing

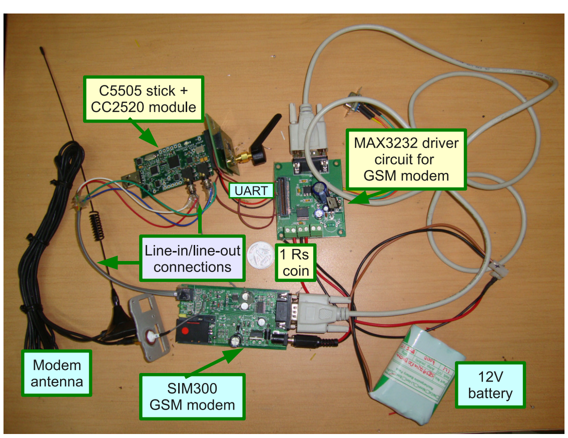

Figure 3: Prototype design of the gateway node

Fig. 3 shows the prototype design of the gateway node. The gateway node has two interfaces: (1) 802.15.4 interface (2) GSM interface. The 802.15.4 interface acts as the identity of the gateway inside the Lo^3 network whereas GSM interface which has a SIM (Subscriber Identification Module) card of a service provider, acts as the identity of the gateway (and the Lo^3 network) in the outside world. Like in our handset [14], we use the TI's C5505/15 hardware and software platform. This platform is integrated with CC2520 radio module to have the 802.15.4 interface. We interface a SIM300 GSM modem [8] to C5505/15 over UART, using a MAX3232 driver circuit as shown in the Fig. 3. The figure also shows a 12V battery, which is used to power up the USB stick and the GSM modem.

With two interfaces, an important and interesting question here is how to translate an 802.15.4 voice packet into a GSM voice packet. On first thought, it may seem that this translation entails decoding the 802.15.4 voice packet at the gateway and re-encoding using a GSM codec, in the software, before sending it over the GSM interface. However, such a re-encoding is not required and the way we do the translation is shown in Fig 3 (see the arrow pointed by 'line-in/line-out connections'). See the simplified block diagram of the gateway prototype in Fig. 4.

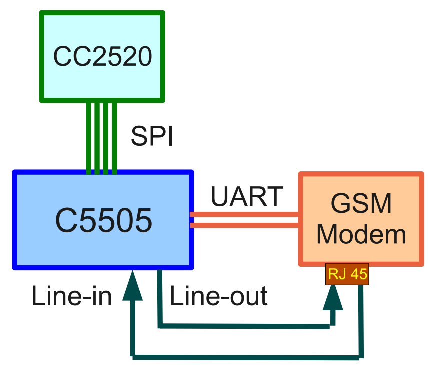

Figure 4: Block diagram of gateway prototype

The C5505/15 USB stick has a line-in and a line-out pin. In our handset (where we have used the same platform), we use these pins to speak (using microphone) and listen to (using speaker) the voice call. For the gateway node, we connect these pins to the GSM modem. The GSM modem has an RJ-45 connector (which has 4 pins) to which an analog headset can be connected to speak (requires 2 out of 4 pins) and listen to (requires remaining 2 pins). For the gateway node, we connect the line-in of the C5505/15 USB stick to the 2 pins of the RJ-45 connector. Similarly, we connnect the line-out to the other 2 pins of the RJ-45 connector. This can stream the voice into and out of the GSM modem.

Thus, when a voice packet is received from the Lo^3 network, we simply decode it and play it through the line-out. This acts as line-in to the GSM modem which encodes the voice and sends it over the air. Similarly, when a packet is received at the GSM modem, it is decoded at the GSM modem and played back using its line-out, which acts as line-in for the C5505/15 stick. At C5505/15, this voice is sampled, encoded (using Speex codec) and the voice packet is routed to the Lo^3 network. This is shown in Fig. 5.

5.2 Software interfacing

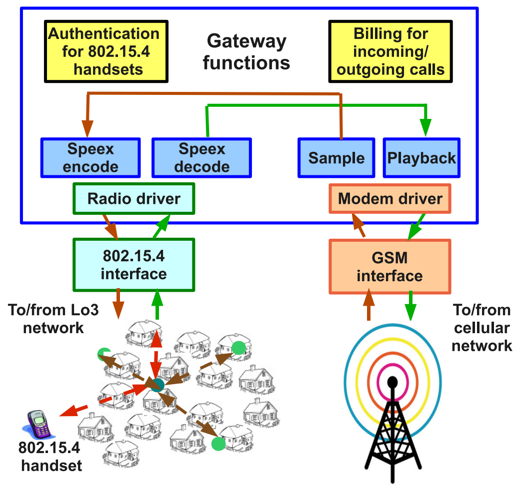

Figure 5: Functionalities of the gateway node

As shown in Fig. 5, in our gateway node implementation, we have a radio driver to control the 802.15.4 interface (CC2520 radio). Similarly, we have implemented a modem driver to control the GSM modem through the software. The CC2520 radio driver lets us control the transmission and reception of an 802.15.4 packet. Using the modem driver, we can invoke various modem commands (e.g. call dial, call answer, call status) during call set up or tear down.

In addition to the above drivers, we have a Speex codec module. This module is an implementation of the open source Speex codec for the C5505/15 platform (provided to us by CouthIT [2]). We use 5.9 kbps codec which generates 15 bytes for every 20 ms of voice samples. In our LiT MAC implementation [13], we have a TDMA frame of 60 ms and currently we use this frame length as the repeating pattern for the schedule. That is, the time slot and channel allocation repeats across the 60 ms frames and a handset and a gateway is allocated slots every 60 ms. Now, before encoding, we sample 60 ms of voice at 8 khz frequency (480 samples per 60 ms, 1 byte each). This sample is then encoded using the Speex codec which generates 45 bytes of encoded data for 60 ms voice. In our TDMA frame of 60 ms, we have a data slot duration of about 6 ms and with respect to 250 kbps data rate of the 802.15.4 CC2520 radio, the 45 bytes packet fits well in the 6 ms slot. Our codec module implements the ping-pong buffering mechanism [6] to do sampling and encoding (and decoding and playback) activities simultenously.

Interaction with LiT MAC: Note that, the gateway node is a part of the Lo^3 network and it runs the LiT MAC protocol [13]. As the part of the LiT MAC, a schedule needs to be established before the flow of voice packets begins in the Lo^3 network. The schedule contains the time slot and channel assignment to the nodes part of the active flows in the network. Before the voice transfer between the handset and the gateway node begins, a flow is established between the two and the corresponding TDMA schedule is conveyed to the intermediate nodes in the network. In the schedule, the gateway node is allocated one slot for the transmission into the Lo^3 network and one slot for the reception from the Lo^3 network. The schedule dissemination in LiT MAC implicitly conveys the routing path for the flow in the network [13]. Thus, a packet is appropriately routed to the gateway node from the handset and from the gateway node to the handset.

5.3 Call routing

In this subsection, we explain the overall sequence of the activities in establishing a call from a handset inside the network to a phone in the outside world. Here we assume that a flow from the handset to the gateway node (segment of the call inside the Lo^3 network) is already established.

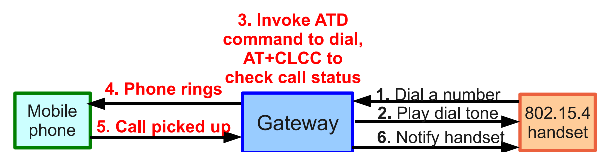

Figure 6: Call from the Lo^3 handset to the outside phone

Fig. 6 shows the sequence of activities when a call originates from the handset inside the Lo^3 network to a phone in the outside network. First, the callee dials the phone number and sends the request to the gateway node. The gateway node responds with a dial tone. The gateway node then invokes ATD command to dial the number, and after dialing the number, it checks the call status (dialed, ringing, answered) till the call is answered. When the call is picked up by the phone in outside network, a notification is sent to the handset in the Lo^3 network. This establishes the bidirectional real-time voice call. When the callee or the caller hangs up the call, the connection is torn down at the gateway and subsequently the flow in the Lo^3 network is terminated.

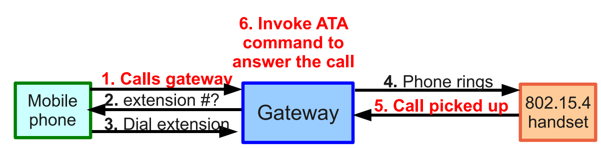

Figure 7: Call from phone outside the network to Lo^3 handset

Fig. 7 shows the sequence of activities when a call is dialed from a phone outside the network to the handset inside the Lo^3 network. First, the phone dials the gateway node (which is an identity of the Lo^3 network to the outside work). The gateway, in response asks the phone to dial an extesion number. This extension number is the ID of the handset inside the Lo^3 network. Once the extension is dialed, the gateway establishes a flow in the local network and contacts the handset. When the handset picks up the call, the gateway invokes the ATA command which answers the call.

5.4 Authentication and billing module

Since the voice calls travel from/to the outside network, for the security reasons, the gateway node needs to keep track of the originating or terminating handset in the Lo^3 network. To provide such a functionality, we can run an authentication protocol over LiT-MAC which authenticates every handset to the gateway node. The gateway node then can log the statistics about the call, for example, the call duration. The call duration can be used to charge each handset node for the incoming or outgoing calls at the end of a week or a month.

5.5 Future work

The text in bold in Fig 6 and 7 signifies implementation in current prototype of the gateway node. Currently, we dial a pre-determined phone number from the gateway node. Implementing a dialing facility is a part of the future work. Also, currently we redirect the call to a pre-determined handset and we intend to implement an extension facility in next version of the prototype. Adding an authentication and billing functionality into our prototype is also a part of the future work.

6. PILOT DEPLOYMENT

We now present details of our pilot deployment in Ahupe village, near Mumbai, India. The village is situated on the top of a mountain as shown in Fig. 8. There are a few points of cellular connectivitiy on the mountain edge as shown in the figure. However, there is no cellular coverage inside the village. The village is spread over a set of 5 groups over 1.2 sq.km, each comprising of about 50 households. A group is spaced by about 300m from other groups. The village has a population of about 1200, and the average income of the village is about \$2 per day. The village has an average 8 hours of electricity supply per day.

For our pilot deployment, we had the following goals. (1) Establish a multi-hop bidirectional local voice call within the village. (2) Establish a bidirectional voice call from/to the village to/from the outside world. (3) Evaluate the quality of voice. (4) Take feedback from the villagers about the overall system.

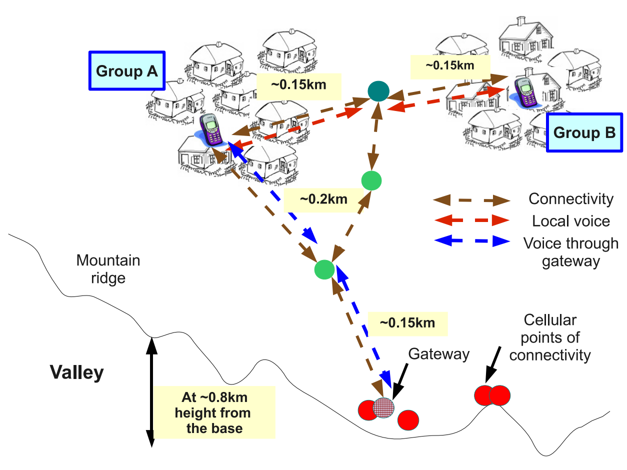

Figure 8: Pilot deployment at Ahupe

Our set up in this village is comprised of two handsets, three infrastructure nodes (these are Telosb motes), and one gateway node. We connect an 8 dBi omni-directional external antenna to the Telosb motes. We refer to a mote connected to an external antenna as the infrastructure node. The infrastructure node transmits with 0 dBm power (maximum power level of CC2420 radio). Our in-campus experiments show that when the infrastructure node is kept at 3 m height, we get a reasonably good signal strength (better than −85 dB) at a distance of about 200m. When the node is mounted on a roof-top of a building (to get sufficient ground clearance), we achieve a link distance of more than 350m. A similar observation is made in [11].

Experiments at Ahupe: We repeated the in-campus experiments at the village site and observed the similar link characteristics. As shown in Fig. 8, we could connect two houses, one in group A and other in group B, by placing an infrastucture node in between and keeping handsets at two houses. The length of the two links is about 150m. Further, as shown in Fig. 8, the distance between the cellular point of connectivity and the village is about 350m and we repeated the similar set up to connect a handset in group A to the gateway node.

With this set up, we successfully established several real-time local voice calls between the two handsets. Each call lasted for around 2 minutes. We measured the percentage of packet drops (for a window of 100 packets) and the resulting jitter. The maximum packet drop was 3% and the corresponding jitter was 180 ms. However, the average packet drop was close to 0%, and the average jitter was 0ms. This shows that the links of the network were quite stable and the voice call did not experience any quality issues. We had two villagers to take over a call. The villagers were quite satisfied with the quality of the voice.

We also dialed several phone calls successfully from our handset in group A to the phones in the outside network, for example, a mobile phone of a colleague in our university lab at Mumbai, a fixed-line telephone of the clinic of which the villagers seek help in case of medical emergency. These calls, through the gateway node, lasted for several minutes. We also received calls from the outside network and routed the call to the handset in group A. Here too, the villagers were happy with the quality of voice. The villagers seemed delighted with the hope of receiving the calls at their doorsteps.

We observed that there is a small delay in the real-time voice streaming between the handset and the phone outside the network. This is a cumulative delay comprised of following components: 60 ms voice sampling at the handset, 60 ms frame to transmit the voice packet in Lo^3 network, 60 ms playback at the gateway node and the delay in the backhaul network.

7. COST AND POWER REQUIREMENTS

We now quantify the cost and power requirements of the gateway node. The off-the-shelf C5505/15 platform costs \$49 [9], the CC2520 802.15.4 radio costs \$2 [1] and the GSM modem costs \$50. A 12V battery to power the gateway node costs \$20. With the initial service cost, add-on PCBs and connectors, the overall cost of the gateway node is \$140. This is much cheaper than the alternative technologies like OpenBTS.

In terms of power, The C5505/15 platform consumes about 200 mW (sleep mode power of < 1 mW), the CC2520 802.15.4 radio requires 100 mW (at maximum 5 dBm power) (sleep mode power of < 1 mW), and the GSM modem demands 1 W. Thus the the overall power consumption of the gateway node is 1.3 W. For an aggregate call duration of 12 hours per day and a 20% duty cycling [13] of the C5505/15 and CC2520 radio (which have duty cyling support), the power consumption per day is $(0.3 \times 12\text{H}) + (0.002 \times 12\text{H}) + (1 \times 24\text{H}) = 27.62$WH. With a 4.5AH, 12V battery, the gateway node can effectively operate on $4.5 \times 12/27.62 \approx 2$ days. Thus the gateway node can continuously operate for

2 days without relying on the power off the grid. In comparison, alternatives to our gateway node demand substantial battery back-up.

8. DISCUSSION

A natural question to ask is why not use a GSM cell phone as the gateway's main building block, rather than a GSM modem, since it could be cheaper due to more commodity? We observed that not every low cost cell phone gives flexibility in terms of programming and interfacing, e.g. interfacing a cell phone to TI's C5515 USB stick over UART is not possible with most of the low cost cell phones. In fact, very few phones have hardware interfaces exposed and programming tools available; functionalities required to be part of our gateway node.

Another important question to ask with respect to Lo^3 network is: does the delay of voice packets increase linearly with the number of hops? The answer is yes with a few interesting observations Firstly, note that several hops can be scheduled in a TDMA frame and if the TDMA schedule spans across multiple frames, the delay, in terms of a frame size, is a step function with respect to the number of hops. For instance, in our case, we have a 60 ms frame and a typical value of tolerable end-to-end delay is about 300 ms [16], for a real-time voice call. And we can schedule number of hops in a frame. Secondly, the scheduling delay also depends on the order in which consecutive links are scheduled, and with careful scheduling [12], we can cover sufficient number of hops in Lo^3 network, within the given delay constraint.

Given the low data rate (250 kbps) of 802.15.4 technology, another natural question in terms of scalability is how many simultaneous calls can be handled by the various elements in the network? In [13], we showed that an infrastructure node in Lo^3 network can support two simultaneous bidirectional voice calls through it, and at a given instance, there could be several calls in progress in the network. Also in terms of reliability of the links, evaluation in our outdoor testbed in [13] showed that 802.15.4 links remain stable when operated above a threshold. This is also ascertained by the smooth streaming of voice packets in our pilot deployment.

In our deployment, we measured the delay and jitter variations to quantify the voice quality. In our future work, we would like to qualitatively evaluate the voice quality using well-known metrics like MOS. Also we plan to deploy our network for several days in the same village with about 15 to 20 infrastructure nodes and sizeable number of handsets. Network measurement study of such a full-fledged deployment is also part of our future work.

9. CONCLUSION

In this work, we considered the goal of extending the cellular coverage inside the remote villages using the nearby points of cellular connectivity. We presented the case of a low cost and low power gateway, which can connect a remote village to the cellular backhaul. The gateway interacts with an 802.15.4 network and routes calls from the 802.15.4 handsets into the outside world. The gateway has a GSM interface to connect to the cellular backhaul. We deployed this system in a village, near Mumbai, India and established several voice calls successfully from the village to the phones in the outside network. We also established several local voice calls within the village. Our deployment experience was very much hassle-free and this was largely due to the small form-factor and power efficient 802.15.4 devices. We received a very positive response to our system from the villagers. We believe that apart from the applicability in the developing regions, such a system can be used by the cellular service providers to extend the cellular connectivity over a larger geographical area.

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