An Experiment in Reducing Cellular Base Station Power Draw With Virtual Coverage

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ABSTRACT

Lack of access to cellular service often goes hand-in-hand with lack of access to power. For example, the GSM Association estimates that 95% of people living without cellular access in East Africa also lack access to grid power. This situation forces cellular network operators to build out power infrastructure along with their network infrastructure, dramatically increasing costs. While numerous equipment providers offer "low-power" GSM Base Stations (BTS) for use with renewable energy sources, these have a power floor of roughly 70W, which still necessitates a large upfront expenditure. The naïve solution to this problem is duty-cycling—simply turning off the equipment for portions of the day, usually at night. This commonly-adopted approach prevents important use cases such as all-hours emergency calling.

Recently, we proposed a technique called *virtual coverage* to provide on-demand cellular coverage by introducing a "sleep" mode for cellular equipment. The solution turns off the BTS during low-utilization periods, but allows users to power the system back on using specialized autonomous radios if they need to communicate. Incoming communications also wake the BTS, facilitating two-way correspondence. While a potential solution, no real-world deployments have yet validated virtual coverage.

The core goal of this work is do just that; we utilize virtual coverage to provide both low power consumption and on-demand access in a real cellular network during a six-month deployment in rural Papua, Indonesia. We demonstrate that the system was used and understood by customers, with more than half of subscribers using the system during "night" (i.e., on-battery) hours, making 730 outbound and receiving 755 inbound communications. Our scheme also allowed the BTS to be in low-power mode for 87% of night hours, reducing night power draw by 56.6%. We believe these results demonstrate that virtual coverage is a viable solution for reducing power draw in rural cellular networks.

ACM DEV 4, December 06 — 07 2013, Cape Town, South Africa

Categories and Subject Descriptors

C.4 [**Computer Systems Organization**]: Performance of Systems—*Design Studies*

General Terms

Information and Communications Technology for Development

1. INTRODUCTION

Cellular telephony is one of the most impactful technologies of the 20th century, with over six billion users throughout the world [21], up from just 3 billion in 2008 [11]. However, hundreds of millions of people who live in remote rural areas are still without cellular network coverage. Bringing network to these areas can also be a boon to users, reducing information asymmetries [23], bringing services such as banking [20, 25], and a variety of other economic benefits [8, 34].

Unfortunately, these areas are without coverage for one primary reason: economics. It's simply too expensive for incumbent providers to enter these remote and rural markets. The primary cost is power; the GSM Association (GSMA) estimates that 95% of the people without cellular coverage in East Africa also lack grid power [12]. Similarly, the ITU estimates that 50% of the operating expense (OPEX) of a rural cellular network is power-related [22]. This is because many rural towers are powered with diesel generators, requiring constant trips to refill reservoirs, roads to support these trips, and fences to protect the valuable fuel and equipment.

For these reasons, powering cellular equipment with renewable energy sources could change the economics of building rural cellular infrastructure and bring coverage to many currently unserved parts of the world. Multiple vendors, including Range Networks [29], Vanu [33], and Altobridge [4] provide cellular equipment for this very purpose. Unfortunately, the equipment sold by these providers draw more than 70 watts of power. Though "low-power" compared to traditional hardware, powering a 70W BTS solely with renewable energy can be difficult, potentially requiring over fifteen 70-pound deep-cycle batteries per BTS site and increasing the total installation cost by up to fifteen thousand dollars [15].

The traditional answer to this problem is duty cycling: powering down the equipment when not in use [2]. With solar solutions, duty cycling usually takes place at night, when power is unavailable. Users generally dislike this solution as it greatly limits emergency service (a key use case [18]) and other scenarios where timely communication is desirable.

To address these concerns, we developed "virtual coverage" [15], which is essentially a smart duty cycling mechanism. Instead of naïvely turning off equipment, the BTS turns itself off ("sleeps") when not in use. It "wakes" when a user takes an action, such as pressing a button on an autonomous radio called the Wake-Up Radio (WUR). It also "wakes" on incoming communications, such as SMS or voice calls directed to users on the network. When "woken", the network stays active for some period of time, enabling communications by subscribers during this period. The network goes back into "sleep" mode, reducing its power draw, after a pre-configured idle time, i.e., period in which no SMS or call is initiated or received.

We believe virtual coverage has the potential to bring cellular coverage to underserved rural areas throughout the world. Unfortunately, there has never been a real-world deployment of the technology, only simulations on existing cellular networks. This means core usability questions remain unanswered: How will the technology be received? Will people use it at night? Will it fill their communication needs?

The main contribution of this work is to answer these questions. We implemented and deployed a cellular network utilizing virtual coverage in rural Papua, Indonesia. The network was installed in February, 2012, with three WURs installed in high-traffic parts of the village. The network services 170 paying users as of July 2013. Both SMS and voice services were offered locally, but outbound communications were SMS-only. Using the concept of virtual coverage, the network was put into "sleep" mode from 23:00–06:00, roughly the period of time when the grid power (a microhydro installation) wasn't available each night. During this time, if the network was "asleep", the users would need to walk to a central location and press a button on the WUR to "wake" the BTS. Alternatively, incoming SMS (from outside the village) would wake the BTS to enable delivery of the SMS.

During our six month trial, we saw 1485 total communications in the "sleep" periods, with 730 (49.2%) being initiated by and 755 (50.1%) received by people in Desa. The BTS itself was "woken" from sleep a total of 428 unique times, with 59 (14%) being caused by local users pressing the button and 369 (86%) by incoming SMS. Night service was used widely with 86 out of 170 (50.6%) of the subscribers making use of the network during the night period. 76 of these sent at least one unsolicited SMS, indicating that this participation was not only passive. Lastly, even though we were able to provide connectivity overnight, the network remained "asleep" for 87% of the night, reducing the night power draw by 56.6%. We believe these results demonstrate that virtual coverage is usable, meets a user need, and achieves the goal of reducing network power draw. Moreover, it is clear that virtual coverage has the potential to enable the deployment of renewable-powered cellular infrastructure in areas currently without coverage.

2. RELATED WORK

2.1 Rural Power

Researchers have explored the issue of powering rural networks. Surana et al. [31, 32] worked in the context of IEEE 802.11 wireless networks and found that unreliable grid power was a major limitation. This drives much of our desire for operation with autonomous renewable energy sources.

This work is an extension of our earlier work on virtual coverage [15]. Instead of only conducting a trace-based analysis of the power-saving technique developed, in this work we implement and deploy the technology in a rural area utilizing a renewable energy source. Bhaumik et al. [6] and Peng et al. [28] explored similar mechanisms for saving energy in urban networks. These are not relevant in rural areas, as they assume overlapping cellular stations.

2.2 Rural Cellular

A variety of researchers have explored and deployed custom cellular networks in the developing world [5, 16, 17, 35]. These works, as ours, build off of prior research in economics and development advocating for these smaller-scale networks [10]. Rather than evaluating the user experience of the network, as in prior work, this paper focuses on the impact of virtual coverage on the power draw of a rural cellular network.

Zuckerman argued for using IEEE 802.11 mesh networks to provide basic telephony in rural areas [36]. The Village Telco [3] has built many such networks. It is our experience [14] that IEEE 802.11 mesh networks are not well suited for voice and SMS service, fail to utilize the existing cell phone markets, and are difficult to maintain due to their decentralized nature. As such, our focus is on GSM networks.

2.3 Social Factors

The cellular revolution has spurred a variety of research on the impact of phones on people's lives. Aside from the work showing economic benefits described in the introduction [8, 34], researchers have also explored using these networks to achieve social goals. Avaaj Otalo [27] built a voice mailing list to teach farmers about proper agricultural techniques. Luk et al. [24] explored remote medical consultation. ODK [13] is a toolkit for mobile data collection. Our system, by bringing telecommunications to areas currently without coverage, has the potential to broaden the range of such technologies.

This work also leverages research on the rural cellular experience. Heimerl et al. reported that users in rural areas know more about their cellular networks [19] and are more active in finding coverage [18]. Similarly, Donner [9] and Sambasivan et al. [30] found that people in developing regions often expend considerable effort to achieve fundamental wants: communication or media consumption. This informs our design, implying that basic communications are important enough to warrant the effort of walking to a WUR in order to use the cellular network.

3. CONTEXT

We deployed a cellular network with virtual coverage in a missionary school located in the village of Desa in highlands of Papua, Indonesia in the beginning of 2013. In this section, we detail the environment surrounding our intervention. As this work focuses on the technical details of saving power in rural cellular sites, we avoid the non-technical factors, such as economics and demographics, impacting our system. This is not because we do not find these to be valuable, but rather that our earlier work is better suited to discuss the myriad of economic and social factors present in Papua [17].

3.1 Location

Our intervention took place in the village of Desa in Papua, Indonesia. Papua itself refers to the western half of the island of New Guinea. Papua is shown in Figure 1, with the autonomous state of Papua New Guinea to its east. Papua has officially been a province of Indonesia since being annexed in 1969. Though the second largest island on earth, it is extremely sparsely settled with population density of a mere 8.9 people per square kilometer [7], mostly located in its capital city of Jayapura, on the coast. How-

Figure 1: Papua, Indonesia

Figure 2: The hydroelectric generator and water reservoir.

ever, the population is rapidly growing as Indonesians from other islands migrate to Papua.

Desa itself is located in the Central Highlands, a mountainous region running in a strip through the center of the island. The commercial and administrative center of the highlands is Wamena, host to a military base, airport, grid power, and numerous Internet service providers. This airport is the primary mechanism for transport to and from the highlands, as there are no roads connecting Wamena to other major cities in Papua. Similarly, there is no wired network connectivity to other cities, or even off the island of New Guinea; all Internet access uses satellite links.

Desa is a small community approximately four hours, by road, from Wamena. It has no community-wide Internet or power. Desa is the seat of a district and governs other nearby communities. The area lacks demographic statistics, though we estimate the population to be 1,500 people. Desa was an early center for missionary work in the highlands and has partially retained this status as a center for church organization. As such, the church remains an important organization in the community, playing key role in local politics and authority. The church-owned school Misionaris Sekolahin (MS) is our partner in Desa. The school is run by an American couple who have lived in Papua for over a decade and is funded primarily through donations from abroad. MS considers itself an "international school" and teaches to international standards. The school maintains a high status in Desa, with many important community members' children attending.

3.2 Infrastructure

Being located in an extremely rural area, infrastructure in Desa is lacking. Though there was a community-managed power grid in the 1970's, that system fell into disuse and is no longer functional. The low population density has discouraged cellular operators from entering the market in Desa. Anecdotal stories from nearby communities indicate that Telkomsel, the major Indonesian carrier, charges between five hundred thousand to one million US dollars for a tower installation in the rural parts of the central highlands such as Desa. For this reason, there are no network operators in the area. The closest available coverage is a four hour drive, and US $40 round trip fare, to Wamena, or a four hour hike up a nearby mountain which receives coverage from a larger community over the ridge. It is common for local people to visit Wamena to fulfill their communication needs.

In spite of this, some power and network infrastructure does exist. Of most import is a 5kVA micro-hydro installed by Misionaris Sekolahin years ago, shown in Figure 2. This generator effectively functions as the "grid", with power inverted, distributed, and provided to the approximately 5 school buildings via wall adapters. It powers many pieces of equipment: tens of light bulbs, a dozen laptops, a projector, a refrigerator, and a copier. Unfortunately, the hydro consumes more water than the local stream produces, requiring the refilling of a reservoir (shown in Figure 2) every night. The hydro power is unavailable from around 22:00 every night until 06:00 to facilitate the refilling. An operator manually shuts the generator off and starts it at these times. The reservoir filter clogs during heavy rain, which happens often. These clogs cause the hydro reservoir to empty quicker and cause power outages to happen during the day. They are cleared by a maintenance worker when discovered, but the reservoir would again need to filled before the generator can operate. This happened around ten times in our six months in Desa.

MS also provides VSAT Internet for teachers and students. Students are given Internet to access educational games and content during school hours. Teachers are provided Internet to support their teaching duties, such as finding material online. Internet access is also used to keep the teachers in Desa; most are from other communities in Papua and would leave Desa often if unable to communicate with friends and family back home. Other important people in Desa are given Internet access for similar reasons. For example, the local doctor communicates with his family in Jakarta multiple times per week using the shared VSAT.

Because of the nightly power shutdown and periodic power failures, mission-critical equipment is placed on battery backup. This includes the VSAT and copier. The battery backup consists of a charge controller and a bank of two deep-cycle batteries. While we were present in Desa, MS discovered that the copier was causing voltage drops that would disable Internet access when the grid was down and battery power was low. They increased the battery bank to four batteries to resolve the problem.

4. SYSTEM

Though the general architecture of a virtual coverage cellular system is described in prior work [15], a real-world deployment of the technology required many tweaks and customizations. In this section, we describe the design, implementation, deployment, and operational use of a real-world virtual coverage-enabled cellular network in Desa, Papua, Indonesia.

4.1 System Implementation

We began our implementation with a setup identical to the system described in our earlier work [15]: a 10W Range Networks [29]

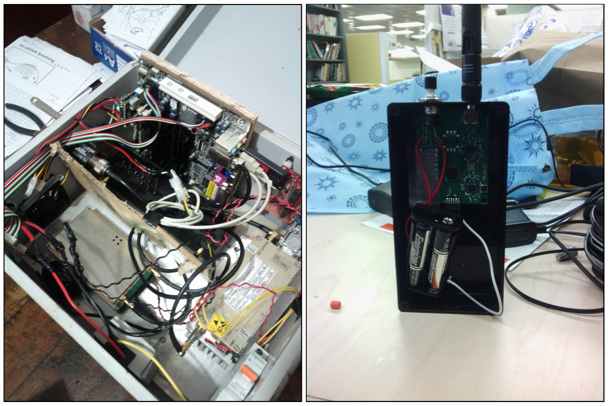

Figure 3: The hardware: a BTS and a Wake-Up radio.

5150 GSM Base Station running a modified version of the public release of OpenBTS [26] available on our Github [1]. We also modified the hardware in a similar fashion, with a high-amperage USB switch connected to the amplifier. We fabricated ten Wake-Up Radios (WUR); the schematics and PCB board layout are also available on our Github.

The system operated as described in our earlier work [15]: it would "sleep" (i.e., turn off the power amplifier) when not in use. It could be "woken" by a user pressing the large red button on the WUR. This communication happens on the BTS's uplink channel, which will be empty if there is no active communication in the network. After "waking", the BTS would stay awake for a configurable length of time, originally three minutes. Any BTS communications, call or SMS, would cause this timer to reset and the BTS to stay awake longer. The BTS would also "wake" if there was an incoming call directed to a user on the BTS.

Our first modification to this basic design was the addition of a "duty cycling" mechanism that was based on time of day, instead of being based only on network activity. The BTS would stay awake during grid-power-available hours regardless of whether there was active communication. The reason for this is obvious: during the day there is grid power and we should utilize it. After the conclusion of grid power, the BTS was controlled by the "wake-up" mechanism alone.

The "wake-up" mechanism also needed to be modified. Due to network bandwidth limitations, our network only allowed SMS, not calling, for out-of-village communications. Local, in-network calls and SMS were available. Virtual coverage, in its original design, did not support waking the BTS with incoming SMS. We modified the virtual coverage implementation so that any incoming SMS would cause the BTS to wake or the sleep timer to reset.

Because our BTS is so similar to the one in the virtual coverage paper, the power draw of our BTS is identical. Table 1 describes the power draw of the BTS and each component in it. The most important factor to note is the power savings: the BTS draws just 25W when "asleep", a savings of 65.2% over the "awake" state.

4.2 Configuration

Having modified virtual coverage to meet the unique needs of the Desa community, we now turn to its configuration. Our goal with the duty cycling and virtual coverage approach was to allow the maximum amount of communication while minimizing the amount of power draw on the battery bank. This design presents us with three configurable variables:

- When the BTS awakes every morning;

Component	Power Draw	%
Radio	12 Watts	17.4%
CPU	12 Watts	17.4%
10W Amplifier	45 Watts	65.2%
Total BTS ("Awake")	70 Watts	100%
Total BTS ("Asleep")	25 Watts	34.8%

Table 1: Power Draw of our BTS and each component of the BTS

- When the BTS sleeps every night; and
- How long the BTS must be inactive to go back to sleep.

These were originally set to 06:00, 21:00, and 5 minutes, respectively. We chose 06:00 as that is when electricity was typically turned on and chose 21:00 as that would allow us to ensure that the batteries were charged by giving us an hour of "sleep" time before power was turned off around 22:00. Lastly, we chose 5 minutes of inactivity as the sleep timeout because OpenBTS's SMS server (smqueue) had a 5 minute retransmission timeout such that if a message failed to deliver (perhaps due to the phone not camping quickly enough) smqueue would wait five minutes to try again. We believed that this five minute timeout would ensure that each incoming message would have two chances at being delivered.

Our first change was to push back the night sleep time to 22:00 and then 23:00. There were two reasons for this. First, we noticed that the batteries were charged much earlier in the day than we initially expected and did not need a period of "sleep" to ensure that. Secondly, we noticed that 21:00 was near our peak usage; users seemed to return to their homes as it got dark and communicate with people outside Desa. As maintaining good quality of service was a primary goal, an unlucky period of inactivity could interrupt users' SMS conversations and force them to find a WUR early in the night. After the first few days of the deployment, we moved the end time back by periods of a half of an hour, looking for the time when there was no grid power and usage seemed to slow down. Using this heuristic we eventually ended up at 23:00, which was chosen to be the final "sleep" time.

We used the 5 minute inactivity timer for most of our study. As we began data analysis four months into the deployment, we noticed that there were no response messages to incoming SMS. After doing some math, we discovered that there were *two* timeouts; the first 30 second SMS delivery failure timeout and the 5 minute retransmit timeout, giving a total time of 5 minutes 30 seconds for the second transmission of an SMS. Our 5 minute sleep timeout meant that many incoming SMS might not be delivered before the BTS slept again if the handset did not attach to the BTS within the first thirty seconds, wasting the second timeout. We changed the sleep timeout to 11 minutes 30 seconds to allow for three functional retransmissions. However, a week later we discovered that the primary issue was actually a bug in our data analysis scripts; some users were responding to incoming SMS after all. Despite this, we kept the sleep timeout at 11 minute 30 seconds to maximize the delivery of SMS in the future.

4.3 Deployment

In late October, 2012, we first installed our BTS in a tree near the primary school building (Figure 4). The network was connected to the school VSAT and its battery bank. We also installed a larger charge controller (upgrading from a 120W to a 240W controller) to ensure that the batteries would be completely charged before the grid was turned off. WURs were not in place during this period. The BTS would not wake from incoming SMS, but would sleep,

Figure 4: The installation locations of the BTS and a WUR.

based on inactivity, from 23:00 to 06:00. The network remained closed for four months as we tested and evaluated the install.

On February 11th, 2013, our network opened for customers. On February 25th, we enabled wake-ups from incoming SMS and installed WURs near three stores (known locally as kiosks) in Desa. The goal was to give the impression of "ownership", reducing the chance of theft. The use of the WURs was free. We selected a region roughly forming a triangle around the center of Desa: a kiosk at the north of the main road, a kiosk on the south of the main road, and a kiosk in the central market east of the main road. Each store was owned by a non-Papuan Indonesian, as are most stores in Desa. A broadcast SMS was sent to all users of the network at the time, describing the "sleep" mechanism and the location of the WURs.

5. EVALUATION

We evaluate the system in three core ways. First, we investigate the use of the system and whether subscribers were able to understand and utilize virtual coverage. This is done though an analysis of call records through the night periods, showing the volume of, nature of, and participation in night communications. We then evaluate if our network was able to meet the core goal of virtual coverage: reducing night power consumption. This is done through BTS logs of "sleep" and "wake" events, showing the amount of power saved through the use of virtual coverage. We also consider the actual design of the WUR through observations of its usage. To begin, we first discuss the relevant background system statistics and the methods of data collection.

5.1 Background

While a detailed description of the network's overall usage is outside the scope of this paper, we briefly summarize its key properties. These statistics demonstrate that this network has real subscribers and is an honest assessment of the concept of virtual coverage. The Desa network:

- Serves 170 users in and around Desa with prepaid calling and SMS;
- Supports calls and SMS locally, but supports only SMS for outbound communications;
- Handles approximately 700 SMS and 50 calls per day;
- Has roughly twice as many out-of-village communications as in-village; and
- Delivered roughly 100,000 SMS during the evaluation period.

We emphasize that most communications handled by our BTS happen during the day; the night service provided with virtual coverage is, by its very nature, limited. Desa has no power at night and the majority of the users go to sleep after the sun goes down. The point of virtual coverage is to provide service for instances where users have a pressing need for communications, such as emergencies or other time-sensitive events, while still avoiding the wasted energy of broadcasting during times of low utilization. It is our view that even light night use validates this model.

5.2 Data Collection

This evaluation utilizes two primary data sources. First, each communication attempt in the system is recorded into a "call detail record" (CDR). These are recorded even if the connection fails, as would occur, for instance, for calls or SMS to invalid numbers. These records are used to determine the total number of communications. CDRs were recorded for the entire operation of the BTS: February 11th to the authoring of this work: July 16th.

As a consequence of the network design, there can be multiple "wake-up" events for each new CDR. For instance, a user may use the wake-up radio multiple times before actually sending an SMS. Similarly, a user may send multiple SMS after waking the BTS just once. For these reasons, we use the actual BTS log to determine when the BTS is "awake". Each instance of "sleeping" and "waking" is recorded in this log. Unfortunately, misconfigured log rotation caused us to lose the earliest BTS logs. As such, we only have power measurements from March 24th to July 16th.

5.3 Usage

Using the both the call and BTS logs, we address the core questions about the usability of the system. We first analyze if users were able to make use of the "wake-up" mechanisms, demonstrating their understanding of the basic idea of virtual coverage. We then examine how many users communicated during the "night" periods and in what volume, demonstrating that the technology was actually used by a large portion of the population and therefore presumably useful to the network subscribers in general.

"Wake-up" Usage.

As recorded in the BTS log, the Desa base station was woken from low-power mode a total of 566 times in four months, an average of 4.9 wake-ups per night. This does not include the daily wake-up due to duty cycling or extraneous wake-ups due to reboots. The majority (65%) of wake-ups were triggered by incoming SMS. The remaining 35% of wake-ups were the result of using the WUR button. Most of the WUR events happened concurrently; the user was either holding the button down or pressing it repeatedly. 138 of the wake-ups were repeated, meaning they immediately followed the BTS going to sleeping after a previous WUR burst. Removing these from the analysis leaves 59 independent WUR events. Using these numbers instead, we see 14% of our unique wake-ups were caused by the WUR and the remaining 86% from incoming SMS, as shown in Figure 5. Generally, the BTS woke significantly more from incoming SMS than from the use of the WUR. This is likely because the main island of Indonesia (Java) is 2 time zones behind Papua; our 11pm timeout is only 9pm in Java. It's also possible that actively using the WUR is just less convenient than passively receiving a message.

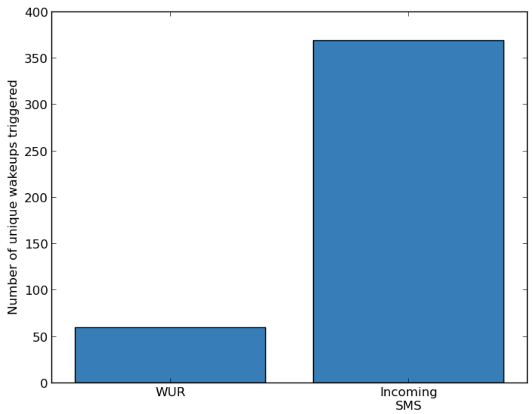

Figure 5: Unique causes of wake-up during night time hours. The majority of wake ups were caused by incoming SMS rather than use of the WUR.

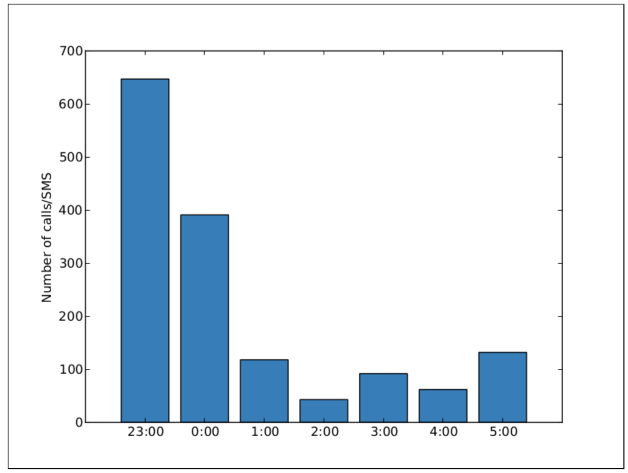

Figure 6: Night hourly usage. While most usage happens in the 23:00 hour, we observed usage at all hours of the night.

Service	Night Use (%)	Day Use (%)
Inbound SMS	755 (50.8%)	31549 (27.0%)
Outbound SMS	390 (26.3%)	36560 (31.2%)
Free Call/SMS	182 (12.3%)	16788 (14.3%)
Local SMS	77 (5.2%)	17972 (15.3%)
Local Call	34 (2.3%)	9104 (7.8%)
Other	47 (3.2%)	3237 (2.7%)
Total	1485 (100%)	117208 (100%)

Table 2: Popularity of services on the BTS for both night and day. "Night" refers to the times when the BTS has been awoken from sleep. "Other" refers to misdialed numbers and attempts to call or send SMS by users with no credits in their account.

Night Network Usage.

Table 2 shows the frequency of each type of communication on the base station, for both day and night, taken from the CDRs. We note that the "night" usage statistics only include communications that took place after the base station entered low-power mode, i.e., actually slept for the first time each day. On days of heavy usage the base station did not enter low power mode until after midnight. In general, there was a large amount of night usage by the community. A total of 1485 messages were sent or received by people in Desa over the evaluation period of six months. 86 individuals used the network during this time, just over half of the total subscriber population. Moreover, 76 of these users sent at least one "unsolicited" SMS or call, initiating a communication without having received any for at least an hour.

The bulk of communications during the night were with contacts outside of Desa (77.1%). This is slightly higher than the same ratio for daytime communications (58.1%). In general, night usage was more focused on external communications than day usage. This isn't surprising; most people in Desa are asleep at night, limiting communication options. Everyone lives within a few kilometers of each other; if you're going to wake someone up, you may actually visit in person rather than send a text, especially if you need to walk to the WUR anyway.

We observed activity at all hours of the night. The bulk of night time usage occurred "early" in the night, shown in Figure 6. Unsurprisingly, this time was close to our peak daily usage period of 19:00 - 21:00. Due to a bug, the BTS was forced to briefly reset itself at 03:00 every morning, "waking" the BTS, and we see a small bump in communications at this time. We note that there are nearly 80 times more communications during the day (117208) than at night (1485). Though the day period is longer than night (17 hours versus 7 hours), this is insufficient to account for the difference. Instead, we believe the night is simply a time when user communication needs are reduced. This supports our design; our goal is to save power during these periods of network idleness. The need to go to a WUR to turn on service also disincentives usage.

These results validate the findings in earlier work [18] that naïve duty cycling does not meet user needs; people in rural areas will occasionally need to communicate with outsiders during periods of relative inactivity. Virtual coverage successfully meets this need.

5.4 Power Savings

One key goal in implementing virtual coverage was to reduce night time power usage of our cellular infrastructure. To evaluate if our system met this goal, we measured power consumption in two ways. First, using the BTS logs we are able to precisely measure the actual power consumption of the base station. Secondly, using the call and SMS records in the CDRs, we calculated an "ideal" power consumption profile. The second method ignores periods where the base station was turned on but not actually used; this situation turned out to be far more common than we expected.

Figure 7 shows the cumulative distribution of hours the base station was active each night (i.e., between 23:00 and 06:00) under each of these models. The BTS remained in low-power mode for the bulk of most nights, with a median "awake" time of 48 minutes per night. In general, below the 90^{th} percentile the actual and ideal power consumption were closely matched, suggesting that power consumption roughly matched what was required for the desired usage. However, we observed a large increase in actual usage over the ideal for nights in which the BTS was turned on the longest.

As stated above, we found six instances where the base station received a sustained burst from one of the WUR for more than 30 minutes, the longest of which lasted over three hours. These events took place throughout the course of our study and were not concentrated only at the beginning. While we cannot be sure, we believe a user may have taped down the switch of a WUR to force the base station to remain on throughout the night. This may have stemmed from a misunderstanding of how virtual coverage works; when the base station is off, handsets will show "no service" to

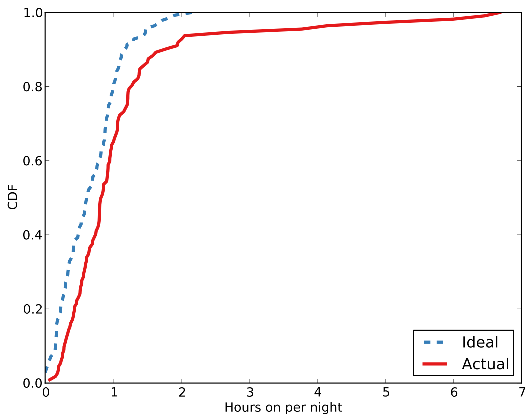

Figure 7: Cumulative distribution of time on per night. The actual and ideal power consumption diverge at the high end due to several instances of the WUR being kept active for several hours, preventing the BTS from going to sleep.

their users. Someone expecting an incoming message could be understandably worried that they may miss their message during this period, even though the base station would have woken up upon its receipt. We hope to further investigate this behavior in the future.

Despite these instances, the system was successful in reducing power consumption and remained in low-power mode for the bulk of each night. In total, virtual coverage allowed the power amplifier to stay off for 87.0% of the night (when hydro power is unavailable) providing 56.6% total power savings at night. In the ideal model where users only wake the BTS when they actually need to communicate, the BTS would be asleep 90.3% of the night. This results indicate that our BTS, by virtue of using virtual coverage, can utilize half the batteries and power generation of a traditional low-power cellular base station.

5.5 WUR Design Findings

In our deployment of the WURs, we found that the basic design of the radio was lacking in two primary ways: the use of the WUR button, and the design of the case.

WUR Button.

The WUR was designed to be as simple as possible; a user walks up, presses the big red button on the case, and the BTS turns on, providing coverage. However, we did not anticipate how users would understand and make use of this simple interface.

When the WUR button is pressed, it broadcasts a radio burst on a specific frequency that is picked up by the BTS. Users understood this, as demonstrated by the numerous wake-up events detected by the network. However, users did not understand the effect on the *battery life* of the WUR. As mentioned above, on six occasions users seemingly **held down** the button for long periods of time, causing it to continuously broadcast and wasting the WUR's battery. We assume this was done because they did not understand that the BTS did not need to be awake for incoming SMS to be delivered. A quick change to the WUR design, causing each *press* of the button to cause a broadcast (instead of broadcasting continually when pressed) would reduce the incentive to do this. We propose other solutions in the discussion.

WUR Case.

The WUR case was designed to be portable, as one potential model of deployment was attaching the radio to individual users or phones [15]. This was a mistake given the way we deployed WURs in Desa; there was no great way to tether the WUR to a specific location. Instead, we only duct taped the radios to covered posts. Despite our best social efforts, one WUR has already been stolen, though this happened near the end of the study and is unlikely to have meaningfully affected any results. A case that had hooks for locks, or zip-ties, or simply just screw holes would be much easier to mount and secure.

6. DISCUSSION

6.1 Study Limitations

The primary limitation of this study is our lack of qualitative data about the use of the network during the "night" period. We have no data concerning the relative value of these communications to the users or the community, only quantitative data on the actual use of the network. This was an unfortunate side effect of the potential nature of talks late at night; they traditionally (at least to us) are more private and sensitive than similar conversations during the day. In short, we felt uncomfortable asking users about their discussions that took place at 03:00. In the future, we hope that this will be resolved through better interpersonal relationships with users so that they might be willing to trust us with this information. As it stands, we were not there yet.

A second limitation concerns the generalizability of the result. The night communication patterns and needs of the people of Desa are likely to differ from those of other communities. For example, in Desa there is no grid power at night; this means that relatively few people are awake and potentially limits the amount of local communication at night. Similarly, Indonesia spans multiple time zones. This likely increases the chances of incoming SMS earlier in the night at Desa (GMT +9), when people are still out and about in Jakarta (GMT +7). Each potential deployment of virtual coverage should assess their own specific communication needs before deploying and configuring the system.

6.2 Holistic Power Savings

We note that, despite the BTS power savings shown in this work, the eventual goal is to reduce the power draw of the entire system. Throughout our earlier virtual coverage work [15] and this work, there is little discussion of the other pieces of infrastructure required for operation. In our case, that would be the VSAT system. Altobridge [4] has developed modifications to the core network protocols to minimize VSAT usage. We believe that it is possible to implement similar power saving techniques in the VSAT, continuing to lower the total power draw of the system.

6.3 Future Work

Despite the positive results shown in this paper, there is more work to do. We focus on four things: industrial design, protocol changes, smarter power amplifier design, and investigating the effect of price changes on night network utilization.

Radio Design.

As mentioned earlier, the project would have benefited from better industrial design: a WUR that only broadcast the wake-up burst for a limited duration for each button press (rather than broadcasting continuously) and better discouraged theft. The team had little experience with user-facing hardware design, and the lesson is well-learned. Our next deployment will use better designs.

Smarter Wake-Up Protocol.

As mentioned in the virtual coverage paper [15], it's possible to use a smarter "wake-up" burst when moving the BTS out of idle mode. We could program a unique ID into the actual burst. This could be used to limit the number of transmissions from any device by ignoring repeat bursts, potentially disincentivizing the above "holding the button down" issue.

Smarter Power Amplifier.

Virtual coverage uses WURs, deployed throughout the community, to enable network access during times of relative inactivity. The users walk to the site of a WUR to "wake" the BTS. This has worked successfully in the Desa deployment site. However, it may be possible to eliminate the need for these devices entirely while still supporting legacy phones and reducing BTS power draw.

We are currently investigating the design of a smarter power amplifier which does duty cycling on a millisecond basis. This would allow us to put it to "sleep" on a per-slot basis, instead of for minutes at a time as we do now. GSM is time-division multiplexed, meaning that each time slot is a different logical channel. When the BTS is operating at low utilization, it may be possible to put the amplifier to "sleep" for just unused channels, while keeping it "awake" for important channels like the beacon channel. This would allow us to build a power-proportional BTS which scales its power consumption linearly based on load. Handsets would see the expected channels (Beacon, Synchronization, and Frequency Correction) and still be able to camp to the BTS and make or receive calls even if most other channels are inactive.

The overall power savings of this design are likely to be comparable to virtual coverage; though we'd still waste power broadcasting control information at times of zero utilization, we'd save more power during times of light utilization where virtual coverage requires the entire power amplifier be awake to handle just one call. This is a promising research agenda and we hope to have a prototype by our next field deployment.

Price Changes.

We are curious how changes in service prices might affect the usage of the WUR. There's two lines of thought on the topic. First, communications should be *more* expensive at night as they require the use of more power infrastructure. Second, communications should be *less* expensive at night as the backhaul network is less congested. We are unsure which is correct, and so we kept prices the same as during daytime operation in this study. It also simplified the analysis. We plan to evaluate the data and eventually attempt to vary the prices to more efficiently use the network and power resources, perhaps changing the prices based on the amount of power in the batteries or the level of network congestion.

7. CONCLUSION

Hundreds of millions of people live in rural areas without cellular coverage. The primary reason for this is economic; it's simply too expensive for operators to install and run cellular equipment in areas without grid power. Researchers and practitioners have explored mechanisms for reducing the power draw of these networks. In this paper, we explored the concept of "virtual coverage" originally presented in our earlier work [15]. In a virtual coverage-enabled cellular network, the equipment enters a low-power state during periods of inactivity. A user can "wake" it, enabling access, using a custom autonomous radio called the Wake-Up Radio (WUR). While there have been theoretical analyses of virtual coverage, there has been no real-world analysis of how users would make use of such a system.

Our core contribution is a real-world deployment of the technology in the village of Desa in Papua, Indonesia. Desa is extremely rural, four hours drive from any existing network coverage and lacking both grid power and wired Internet. The base station was installed in a tree in the center of town supported by WURs installed next to three stores in the community. We opened the network for customers on February 11th, 2013 and monitored its use until July 16th.

In our network, there were 1485 total communications sent during the "night" period, with the BTS being woken from sleep 566 times. People in Desa instigated many of these wake-ups, with 197 wake-ups coming from users in Desa who used the time "awake" to send 730 communications. Eighty-six (50.6%) of the people in Desa sent or received communications during the night period. In total, virtual coverage allowed the Desa network to provide communications at night while being "asleep" for 87% of night-time hours and reducing the night power draw by 56.6%. These results demonstrate that virtual coverage is able to be understood and used by a rural population and also successfully reduced the power draw of a rural cellular network while still supporting 24-hour communications.

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