Research Article

A Longitudinal Study of Local, Sustainable, Small-Scale Cellular Networks

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Abstract

There are more than six billion active cellular subscribers, and they spend more than $1 trillion a year on communications. Despite this, hundreds of millions remain unconnected. One reason for this gap is the top-down nature of traditional networks, with large telecommunications firms deciding where coverage is to be available. This is enforced by the large capital investment required for cellular systems. Recent technological innovations have enabled cheaper cellular equipment. This shift is enabling new models of cellular telephony. Small organizations are suddenly capable of becoming service providers. In this article we ask, "How successful would bottom-up cellular networks be?" Essentially we argue for and demonstrate a local cellular network, employing existing infrastructure to operate at a lower cost and bring coverage to areas traditionally unable to support cellular deployments. We demonstrate this concept with an ongoing 16-month-long field deployment in rural Papua, Indonesia. This network is live, with 349 subscribers providing US$980[1] *per month for the operator. We also show through user interviews that this network provides a valuable service to the community.*

Introduction

There are over six billion cellular subscribers in the world (ITU, 2012). Telecommunication access has an enormous impact on the fundamental economics of their lives (Jensen, 2007) and their communications with friends and family (Burrell, 2008). The impact is particularly large among the disadvantaged; Agüero, de Silva, and Kang (2011) found that, for users at the "bottom of the pyramid," telecommunications displayed the usage patterns of a necessity; as total income falls, the share spent on telecommunications increases, with some disadvantaged groups spending upward of 50% of their income on communications.

Unfortunately, hundreds of millions of others, primarily in rural areas, still lack coverage. The International Telecommunication Union (ITU) estimates that 95% of people in East Africa currently without network coverage are in rural areas without grid power (ITU, n.d.). Galperin and Bar (2006) suggest there is also a structural issue; the only organizations currently capable of deploying cellular networks are major telecommunications

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1. All dollar figures in this article represent U.S. dollars.

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firms. Despite subsidies, these firms' strong profit motive limits their investment in rural connectivity, avoiding areas that are beyond the existing infrastructure or have too sparse a user base. As an alternative model, Galperin and Bar point to microtelcos, small community, NGO-owned, or otherwise independent telecommunications firms that exist in some Latin American countries.

The current model of cellular network deployment is top-down, with governments and large, national-scale telecommunications corporations deciding who gets coverage. Instead, we propose to build bottom-up: local entrepreneurs or NGOs that own and operate their own cellular services for a local population. From an economic perspective, researchers have found that by leveraging existing infrastructure, small-scale local actors can enjoy lower costs than larger ones (Galperin & Bar, 2006). Similarly, decentralizing these networks could potentially empower the local community, increasing opportunities and freedom (Sen, 1999).

We envision cellular networks that are:

- Local, operated primarily by agents within the community;
- Built with existing local infrastructure when available;
- Low-cost, financeable by small entrepreneurs or NGOs; and
- Sustainable, with profits staying in the community.

To evaluate this design, in partnership with two local NGOs, we implemented a small-scale cellular network and deployed it in the village of Desa in rural Papua, Indonesia. This network provides mechanisms for local operation including buying and provisioning SIM cards, buying and selling credits, checking credit levels, communicating with in-network friends via SMS or voice, and making out-of-network contacts via SMS. This network is jointly owned and operated by a local education-focused NGO and a for-profit wireless Internet service provider, providing both a base of operations and the technical knowledge required for sustainable deployment. This is a for-profit network, with our NGO partner charging for both SIM cards as well as credits used for network services.

We monitored the transactions in our network from February 11, 2013 (the opening of the network for sales) until June 15, 2014. In those 16 months, the network serviced 349 users, handled more than 140,000 outbound (out-of-network) SMS, 130,000 inbound (into network) SMS, 100,000 local (in-network) SMS, and 45,000 local calls, generating nearly $1,000 per month in revenue for the operators. We also saw more than 55,000 local service requests, including credit transfers, credit checks, and others, some generating revenue for community members. These results demonstrate the feasibility and sustainability of local cellular networks. Our core contributions are:

- The design of local cellular installations, building off prior nontechnical work (Galperin & Bar, 2006);
- The implementation of a cellular network of that design; and
- The evaluation of the design and its sustainability through a deployment with NGO partners in rural Papua, Indonesia.

Related Work

Local Cellular Networks

Small, local cellular operators are common in some parts of the developed world. For example, the Competitive Carriers Association (CCA, n.d.) is a trade organization for regional cellular operators in the United States. These networks often predate the rise of carriers who now dominate national markets. Although the scale of these local operators is much larger than ours (usually tens to hundreds of towers, instead of one), we argue for a similar model: smaller operators serving their communities profitably.

Galperin and Bar (2006) explored community-owned communication networks in Latin America, arguing for the feasibility of similar cellular systems. We build on this vision by implementing and evaluating an instance of a local cellular system.

Some large aid agencies have proposed using universal service obligation (USO) funds for small-scale extensions to traditional networks maintained by local people (MCIT, n.d.). In this design, the carriers reap all the profit from the installation, in contrast to our approach, in which local actors retain the profits.

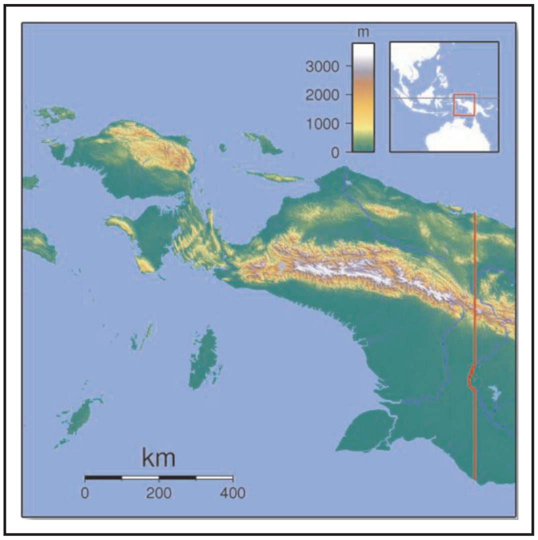

Figure 1. Papua, Indonesia.

Researchers have also explored the use of cellular networks in rural areas. Heimerl and Brewer (2010) and Anand, Pejovic, Belding, and Johnson (2012) proposed building custom OpenBTS (the open source cellular implementation we employ)-based networks for rural areas. Zheleva, Paul, Johnson, and Belding (2013) implemented one such system, deploying it in rural Zambia to support local communications. Hasan et al. (2014) explore technologies and policies to support rural cellular access. Although these designs and implementations inform and improve our system, our goal is fundamentally different: We build and demonstrate a sustainable local cellular network. Lastly, this article is a longitudinal extension of earlier work demonstrating the feasibility of local cellular networks on a shorter time scale (Heimerl, Hasan, Ali, Brewer, & Parikh, 2013). The results remain the same.

Wireless Rural Telephony Networks

Lo3 (Gabale, Mehta, Patani, Ramakrishnan, & Raman, 2013), Serval (Gardner-Stephen & Palaniswamy, 2011), and The Village Telco (Adeyeye & Gardner-Stephen, 2011) use wifi meshes to build low-cost community telephony networks, primarily serving voice. These systems employ custom-made hardware, smartphones, or distributed mesh radios. We use commodity low-cost GSM cellular phones to ease adoption, centralize our installations, ease deployment, and reduce maintenance.

Mobile for Development

With the incredible adoption of cellular systems, both industry and academia have investigated the impact of telephony on rural and developing populations. The ITU has published aggregate usage statistics (ITU, 2012) as well as lower-level analyses of the cost of running a rural cellular site (ITU, n.d.). The GSM Association has done similar work (GSMA, n.d.a).

Researchers have also analyzed cellular use. Jensen (2007) found that the installation of cellular towers in Kerala benefited users by reducing information asymmetries. Waverman, Meschi, and Fuss (2005) and Deloitte (2008) identify other benefits in many developing areas of the world. In general, researchers note that the cellphone has been an important technology in the developing world (Burrell, 2008; Horst & Miller, 2006). These results motivated our desire to provide access.

Context

In mid-2012, a wireless Internet service provider in rural Papua, Indonesia contacted us and asked us to visit and install a low-power GSM base transceiver station (BTS). This was the beginning of our journey into Papua. (Note that the names of all individuals are anonymized.)

Papua

Papua (Figure 1) refers to the western half of New Guinea (and nearby islands) in the southwest Pacific. Often portrayed as isolated, recent developments in Papua have connected the island to maneuvers at the centers of global power such as the UN and the United States (Rutherford, 2009). Major international resource companies are active in Papua, notably at the world's largest gold and copper mine located in the Western Highlands. Various forms of unrest have waxed and waned through the colonial and postcolonial periods (Rutherford, 2009). In 2003, the Indonesian portion of Papua was divided into two provinces, West Papua and Papua, with the independent state of Papua New Guinea to the east. Our work is in the Province of Papua.

Despite being on the second largest island on earth, there are only 2.8 million people in the province, or 8.9 people per square kilometer. The population, however, is growing rapidly due to settlement of migrants from other Indonesian islands. The province faces many societal ills: a low life expectancy of 63.07 years

(BPS, 2013), a low Human Development Index score of 65.36 (BPS, 2013), and a high number of HIV/AIDS cases (Butt, 2005).

The Highlands

Our intervention takes place in the Central Highlands of Papua, located in the Province of Papua. Despite a long history of regional trade connections (Ploeg, 2004), the area had no contact with Westerners until the 20th century, when a scientific expedition happened upon the population in 1938. Following this "discovery," the region was host to extensive missionary activities.

Wamena, the region's commercial and administrative center, is a bustling town with a rapidly growing population and economy, targeted with major state infrastructure investments, and drawing migrants from the surrounding rural area and distant Indonesian islands. This infrastructure is concentrated in the town itself; there are no roads that connect to Papua's other cities, and virtually all goods are brought in by air. A number of companies provide Internet access. A local provider—WamenaCom, run by an Indonesian and an American—is our technical partner for this installation. Connectivity in the Highlands relies on satellites; there are no wired connections to Papua itself. Despite this influx of infrastructure, villages distant from Wamena generally lack village-wide communications or power infrastructure. We installed our network in one such village, Desa.

Desa

Desa is a four-hour drive from Wamena and has neither a cellular network nor village-wide electricity. Administratively, it is the district seat and, thus, the site of government buildings, a police station, a military command center, a health clinic, two churches, a mosque, and government schools, as well as a church-owned private primary school. This church-owned school, *Misionaris Sekolahin* (MS), is our partner in Desa. The school is funded through donations from other countries and run by an American couple (Regis and Nancy), who have lived in Papua for more than a decade. We have been unable to find demographic data for Desa; our estimates place the population at 1,500. While a majority of the population is indigenous, there is a significant migrant population, which includes a number of civil servants, police officers, and soldiers. Agricultural production is the backbone of the regional economy: Farmers harvest produce for subsistence and sale at nearby markets. Desa's economy is shaped by its status as a district center, with cash available from salaries, institutional budgets, and produce sales. Still, Desa is economically and administratively subservient to other centers, in particular Wamena, the largest city in the Highlands, and Karubaga, the regency capital, both located several hours' drive away.

Infrastructure

Prior to our arrival, *Misionaris Sekolahin* (MS) installed a 5kVA micro hydro generator that powers numerous pieces of equipment: tens of light bulbs, 10 laptops, a projector, refrigerators, and other, smaller loads. This hydro is on from 6 A.M. to 10 P.M. daily; it must be stopped at 10 P.M. to allow the water reservoir to recover.

MS also maintains a VSAT Internet connection. Internet access is used primarily by teachers to keep in contact with their friends and family outside of Desa. It is also used for educational purposes, as teachers download informative YouTube videos or share Wikipedia information. A small battery bank with four deep-cycle batteries powers the VSAT and a printer/copier when the hydro is down.

Deployment

In mid-October 2012, we flew to Wamena to join WamenaCom (WC) in bringing cellular access to Desa. WC had been supporting MS for years, providing technical support for the VSAT installed in Desa. This VSAT is intended for school business, but half of the traffic is actually Facebook. This is accepted, as Regis believes that teachers will leave if they cannot communicate with their families.

The team (researchers, WC, and MS) decided that the network would be owned by WamenaCom, with some profits returning to MS as payment for hosting and protecting the equipment. WC provides maintenance for hardware issues, with the researchers resolving software problems.

User Base

Estimating the potential user base in Desa was challenging. We conducted numerous informal interviews and learned that phones were prevalent, despite the lack of coverage. Users claimed to use them primarily for entertainment.

Due to a quirk of GSM's design, we were able to measure the number of unique phones in Desa during the period of our study. Phones attempt to connect to any base transceiver station (BTS, roughly the cellular network itself) if a signal is unavailable; this in order to provide emergency services. We recorded all such attempts to connect for the month of January 2013. During this period, 1,060 unique handsets attempted to connect to our BTS. Of these, 356 were present for five or more days, indicating a sustained presence. Our findings understate total handsets, as many users turn off their handsets while in Desa.

Preparation and Activation

Although we arrived in Papua with a mostly functional system in late October 2012, we spent months resolving technical and social concerns before activating the system. Technical concerns included interconnection failures (with the global telephony system), a drill that damaged a motherboard, and building our billing and management systems. Our social concerns involved community meetings where we asked for feedback and conducted long-term beta tests among some influential villagers. This allowed us to modify our technology to better suit the community and reduce problems before we had paying customers. Eventually, the issues were resolved and the system stabilized. On February 11, 2013 the network opened for business.

System

We built an entire telecommunications company's worth of infrastructure: hardware, billing, and services for our partners and users. The design of our system followed three key principles:

1. Simplicity: Minimize potential failure points.
2. Familiarity: Mimic existing networks when appropriate.
3. Locality: Involve the community in design decisions.

Hardware

Traditional cellular hardware is complicated; instead, we wanted a smaller, lighter, more flexible system. OpenBTS allows us to do this. It eschews the need for a variety of related infrastructure, instead allowing operators to build a complete cellular network using only a commodity PC and appropriate radio equipment. In the ensuing text we detail all the hardware required to run our rural telephone company including the BTS and tower.

Figure 2. Our BTS installation.

Base Station

We purchased a Range Networks RAD1 software-defined radio and mounted it, an x86 PC, a 10W power amplifier, and a 900mhz duplexer in a weatherproof box acquired in Papua. We added a 24V→12V voltage regulator to insulate the machine against power failures and fluctuations (Surana et al., 2008). We tower-mounted the BTS to reduce cabling and RF loss and to protect the hardware from theft. The completed installation is shown in Figure 2. The BTS was plugged into WC's switch for Internet access and attached to their battery bank for overnight power.

Tower Building

Installing a tower in the village is a difficult proposition. Concrete and other building materials are heavy and expensive. Instead, we mounted the BTS on a pole, which we then mounted in a large tree with few branches (see again Figure 2). Other, unrelated wireless equipment, which shares the local VSAT with other locations, is mounted in the same tree.

Network Credits

Unlike prior work (Rhizomatica, n.d.), our network is for-profit; our users pay our NGO partner and affiliates to use it. We believe that local ownership (and local profit) incentivizes local actors to support the network. If local people profit from the network, they are more likely to care when it fails.

Most users in Indonesia use prepaid cellular plans. Local entrepreneurs sell network credits to users for a small premium, giving profit to both the network operator and these entrepreneurs. We built a similar system for the network in Desa. Users pay our NGO partner money for credits which they then use to communicate.

Our NGO partners did not want to sell credits directly to users as this would require too much overhead. Instead, they sell credits to a primary reseller, who then resells the credits to local merchants, who resell them to the users. These resellers (recruited by the primary reseller) set their own prices for credit sales. Each seller in this system makes a profit. The primary reseller only sells in bulk to the other sellers, who sell smaller amounts to local buyers. The primary sellers are two teachers: one Papuan and one non-indigenous Indonesian. The secondary sellers are, at this writing, only non-indigenous people, for a variety of reasons. First, they had the capital to invest (buy credits from the primary reseller). Second, the two secondary sellers each own a local store that has electrical power, allowing them to charge their phones. Lastly, a few of the Papuans with the capital and infrastructure to potentially sell credits have personal or political issues with MS. It is an explicit goal of MS and the researchers to involve local Papuans in this process, and we hope to do so in the future.

Interestingly, this was not the original system. We originally had an indigenous man (whose wife was a teacher at the school) as our only seller. This seller, like all teachers, lived on church property. The church took umbrage at MS operating a commercial service on the church grounds and forced them to stop. This happened when the researchers were away, and the primary reseller and MS decided to set up the current system without researcher participation.

Software Components

Our system is a modified version of the Village Base Station (VBTS; Heimerl & Brewer, 2010). VBTS is a set of extensions to OpenBTS that permits multimodal applications using voice, text, and other mediums. This toolkit, in combination with FreeSWITCH, was used to build all the services discussed below.

Services

A full-scale cellular network provides a variety of functions including voice, SMS, and billing. To provide coverage in Desa, we implemented these and other services: provisioning new numbers, a prepaid credit system (including credit check, transfer, and purchase), number checking, and delivery receipts.

User Provisioning

The first step in our system is selling and providing SIM cards to users. In GSM, SIM cards and phone numbers are separate entities; they must be associated by the network operator.

In our network, SIM cards were purchased from an online vendor, and phone numbers were provided by Nexmo. The least expensive numbers provided by Nexmo are Swedish, which is what we sold to our users. We then used Nexmo to route communications (only SMS traffic as of now to the outside world. This means that all users in our network have Swedish phone numbers, not local Indonesian ones. The reason for this decision is described below.

SIM Cards

Our network provides standard 2G GSM coverage. This means that any existing GSM handset can connect to the network, assuming it has a valid SIM card. What SIMs can connect is a configuration setting in the BTS; we could require specific SIMs or accept any cards. We chose to manufacture our own SIM cards instead of using cards from existing carriers. Only our SIM cards can connect to the network in Desa. We did this to simplify the user's network model; when in Desa, our SIM cards work. When in the larger town, they do not. SIM switching is common in the developing world (Sutherland, 2009) and Indonesia, so this causes no unreasonable hardship.

With this design choice made, we fabricated 1,000 SIM cards (at $0.65 per card) and programmed them with the Indonesian mobile country code (510) and our unique mobile network code (55). Potential customers buy a SIM from our primary reseller at cost, so the reseller makes no profit on that sale. This card is accompanied by documentation detailing the network, duration of service, our communication prices, and services in the network. The card is inserted into a user's phone, and the seller provides a new phone number that is then associated with that SIM.

Our SIM cards are sold with one year of coverage for 100,000 rupiah, approximately $10.30. This price covers one year of number rental from Nexmo ($0.65 per month) as well as the manufacture of the SIM itself ($0.65). Our NGO partner makes approximately $1.80 per SIM sold per year.

Number Provisioning

As mentioned above, we use Nexmo for outbound SMS service. We implemented a mechanism to automatically buy new numbers from Nexmo when provisioning a new SIM card. The system works as follows. When a new SIM card is purchased, the seller places it in the customer's phone and SIM card immediately sends an SMS to 101, signaling its need to join the network. The system queries our user database and our stock of purchased Nexmo numbers. If there is an available number (i.e., purchased from Nexmo but not yet assigned to a user), we assign that number to the user. If no number is available, we purchase a new number (at random) from Nexmo and assign it to the user. The user receives an SMS from 101 with their new phone number. The SIM seller is trained in this procedures; it is not advertised to the community.

Credit System

We use a prepaid credit system similar to that used by other Indonesian cellular providers. To support this, we had to build services for users to buy, check, and transfer credits.

Credit Creation

At the highest level, our NGO partner creates credits in the system to be sold to users for basic communications, which they do via a password-protected Web interface. This service was not originally written by us, but modified from Range Networks' software. After credits are purchased by the primary reseller and added to their account, he or she uses our credit transfer service to resell to secondary sellers. The credit purchase website is only available to the network owner, our NGO partner.

Credit Transfer

After credits are inserted into the primary reseller's account, the reseller sells those newly acquired credits to secondary sellers via credit transfer. Likewise, these secondary sellers use the same system to transfer credits to users.

Credit transfer is initiated by sending a specially formatted SMS to 887. This format is TARGETNUMBER × AMOUNT. If the SMS is incorrectly entered, the user is sent a set of instructions on the correct procedure. If the user has insufficient credit, a message is sent to inform them. If correctly formatted, the user is sent a short message detailing the transfer and asking for confirmation, with a four-digit confirmation code included. If the user responds (again to 887) with the confirmation code, the transfer is complete, and both the buyer and seller are sent a message indicating that the transfer was completed. All SMS are received by the users from 887. The researchers or primary reseller instructed each secondary reseller on how to use the credit system. The service was initially kept from the public, but was advertised via broadcast SMS on May 7, 2013.

Credit Check

To check their current credit level, a user of our system sends an SMS to or calls 888. An SMS response is sent from 888 indicating the user's current credit level. We selected the number 888 because the national telecom provider uses this as its credit check number. This service was advertised to users on the paperwork provided with their SIM card.

Basic Communications

Our network provided both voice and SMS services locally, but only SMS service for outbound communication. The reasons for this are complicated. As mentioned earlier in this discussion, interconnecting with other networks is difficult. Interconnecting with both voice and SMS is even more difficult. Therefore, we decided that we would be able to provide only one such service for bidirectional communication; users would either be able to SMS or call back and forth with their out-of-network friends.

We conducted a series of informal focus groups with people in Desa to find out if they would prefer outbound SMS or voice service. The results surprised the researchers. Although most users communicated primarily through SMS, they preferred to have only voice service if they had to choose. Their reasoning was that some contacts were voice-only (such as older family members), and they wanted the ability to communicate with those contacts.

Concurrently, the limitations of our shared infrastructure were becoming apparent. SMS is asynchronous and can be delayed; voice requires higher bandwidth and service quality. We were unable to provide quality voice service without impacting other VSAT users or changing providers. As a result, we decided for now to support only SMS for two-way out-of-network communications.

Other Services

We opened our network for beta testing in January 2013. Ten key Desa community members, including missionaries, Papuans, and non-Papuan Indonesians, were invited to participate and given free SIM cards. On February 11, 2013, the network opened for general use. During this time we monitored usage and conducted informal interviews. We discovered a few issues and implemented services to remedy these concerns.

Number Check

Our first issue involved users who did not remember their phone numbers. This was probably because they had Swedish numbers, which were strange and looked unlike traditional numbers. To resolve this, we implemented a service for checking one's phone number.

A user sends an SMS to or calls 889, requesting their current number from the system. An SMS response is sent (even if they called) from 889 giving their current phone number. We chose 889 as it is close to 888 and signals that it is a network service. The number check service was advertised on the paperwork provided when a user purchased a SIM card.

Delivery Receipts

The second issue we noticed was one of trust. Users were often uncertain about the status of their messages. Indonesia is rife with SMS-based fraud, including spam and phishing. This fact, coupled with our strange Swedish numbers and the expectation that Desa lacked coverage, meant that many SMS were initially ignored by recipients. Users did not know if the lack of response meant a network failure, a rejection by the receiver, or something else.

To remedy this, we implemented delivery receipts. Delivery receipts inform a user when an SMS has been delivered to the target. We chose to implement the service in an opt-in manner; users signal their participation and then all SMS are given receipts. This choice was made to again mimic the national carrier (or certain handsets) that also use an opt-in model.

To enable delivery receipts, a user sends an SMS to 300. They then receive an SMS from 300 that signals their participation. With delivery receipts enabled, a user would receive receipts again from 300. To disable delivery receipts, a user sends an SMS to 301. As this issue was identified after service activation, delivery receipts were advertised via a broadcast SMS.

Pricing

In collaboration with our NGO partners, we set a pricing scheme for the basic services our system provides. We had three goals.

1. Do not absorb a financial loss on any part of the system. This was because our technical partner, WC, was risk-averse, having had numerous experiences where operations at a loss were abused by users.
2. Make a reasonable profit for the operators.
3. Provide as much coverage as possible to the community.

Table 1 shows the network service prices. Note that nonlocal calls were not implemented. This is due to limited VSAT capacity that degrades call quality. These prices may seem high (outbound communications being roughly three times the national rate), but are justified by the costs discussed in the next section. They are also

Table 1. Services Supported, Their Prices, and Usage Rates.

Service	Shortcode	Price ($)	Usage (%)
Number provisioning	101	free	100
Delivery receipt	300/301	free	14.3
Credit transfer	887	free	29.8
Credit check	888	free	87.7
Number check	889	free	33.5
Local SMS	—	$0.02/sms	80.8
Global SMS	—	$0.09/sms	92.3
Local calls	—	$0.02/min	82.2

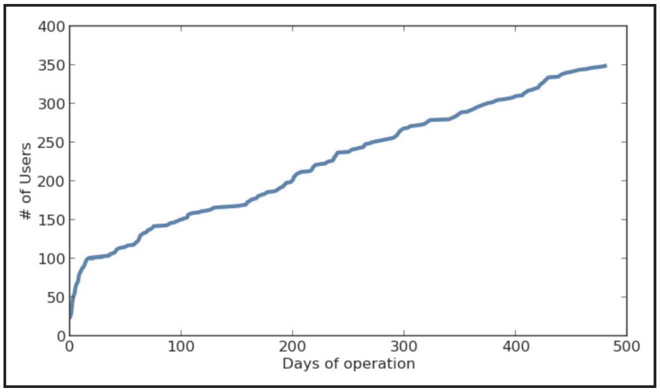

Figure 3. Number of subscribers over time.

not far from those of early networks in Africa (Heimerl, Honicky, Brewer, & Parikh, 2009), which also had limited infrastructure and low population density. We hope to explore other pricing schemes and levels in future work.

Evaluation

The system opened for customers on February 11, 2013, connecting 349 subscribers by June 15, 2014 (Figure 3). To evaluate our system, we gathered usage logs and user interviews. We analyzed the basic system use, which demonstrated significant adoption and use. We then used these measurements, in combination with credit sales and operational costs, to show that the installation was sustainable and profitable for the local stakeholders. Lastly, we conducted user interviews to gather insights into the value the network provided to users, their concerns about its use, and their desires for future features.

Usage

For billing and auditing purposes, we keep records of every call, SMS, and service use. These time-stamped records include the source and destination of every transaction, the transaction type, and associated charges, allowing us to measure network usage.

Figure 4 shows the use of our most important service types over time. This figure excludes calls or SMS made in error (typically attempts made when the user's account was depleted) and the use of free services such as credit checks. Out-of-network SMS was by far the most popular service in our network, with more than 8,000 messages commonly sent per month. Out-of-network SMS to our users (incoming SMS) was tightly correlated with outgoing SMS frequency and comprised our second most popular service type. Local, in-network use began much lower, but spiked in the last few months to become the dominant use of the network.

The general preference for out-of-network communication is not driven by a handful of heavy users. On the contrary, most of our users communicated more with out-of-network contacts than local ones (see Figure 5). Notably, we had more than 40 users who only sent out-of-network SMS compared with no users who sent only local SMS. Similarly, more than 70% of users sent more out-of-network SMS than local. These results persist despite the fact that out-of-network SMS costs more than four times the local SMS.

Table 1 shows the proportion of users who used each network service at least once. Most users (92.3%)

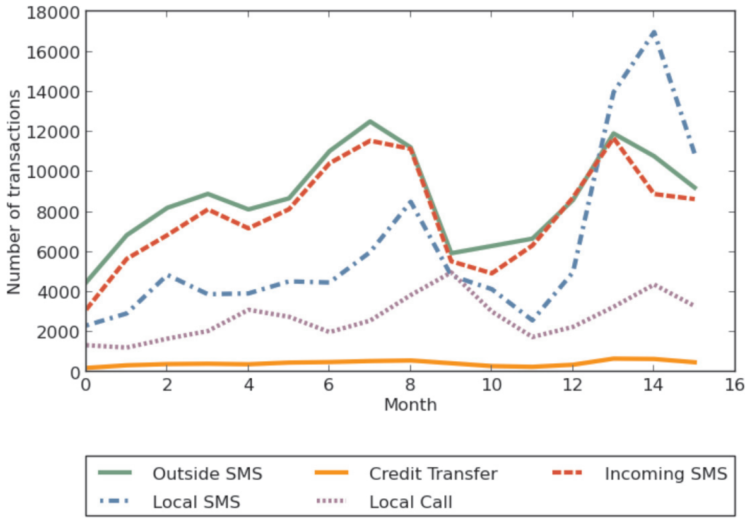

Figure 4. Per-month use of key service types. Out-of-network messaging was most popular.

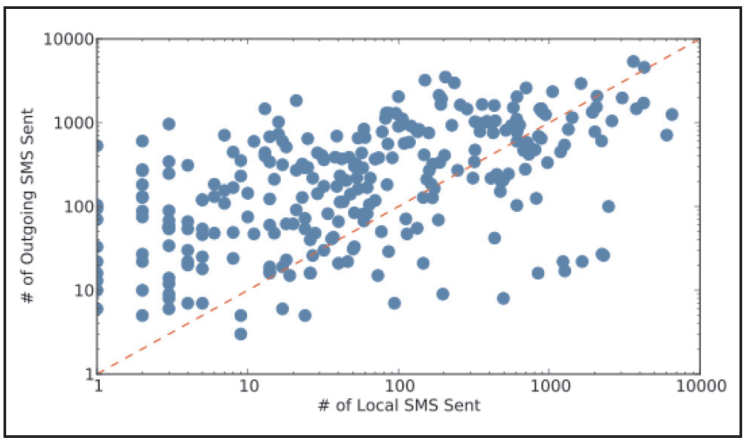

Figure 5. Comparison of in-network vs. out-of-network SMS volume sent per user. Users tend to send more out-of-network (i.e., outside Desa) messages than local ones, although this changed in the final two months of the study.

sent outbound SMS, the most popular network service. While all users received a credit transfer (the only way to purchase credits), 30% of users transferred credit to another user.

Table 2 shows user demographics for the first 100 SIM card sales. This data reflects individuals who bought a SIM card from the primary reseller; we have no way of knowing who actually used the SIM card once purchased. Although there is no census data to compare against, we believe non-Papuan Indonesians and Westerners are modestly overrepresented in the network, presumably because these groups tend to be wealthier. We observed a gender gap between male and female users exceeding the 17% gender gap seen in the rest of Southeast Asia (GSMA, n.d.b). At least part of this gap may be explained by men purchasing SIM cards on behalf of women.

Sustainability

One of our goals was to demonstrate that small, local cellular networks can be financially sustainable. We investigated this by performing an analysis of expenses, revenues, and profitability.

Table 3 describes both the system's capital and operational costs. We consider two infrastructure models: one in which the network shares power and backhaul infrastructure with the community ("shared") and one in which there is no shared infrastructure ("nonshared"). We compute the cost of shared infrastructure as 5% of the capital costs of our partner's VSAT and micro hydro generator; nonshared infrastructure assumes independently purchasing a small VSAT and a solar system with sufficient battery capacity to power both the BTS and VSAT for two days without sunlight. The total capital cost associated with the shared model is $9,650, and the nonshared model $15,900. Maintenance covers wages for a part-time technician to care for the system. Excluding VSAT service, other recurring costs are the same for both models.

The core components of the BTS's cost are the radio and its associated amplifier and duplexer. However, as more companies enter the market for low-cost BTS radio equipment, we expect the costs to fall. On the operational side, backhaul VSAT service is the largest expense. Although connecting a rural community cellular system to the outside world is challenging—typically expensive, low-performance satellite connections are the

Table 2. Demographics of First 100 SIM Card Purchasers (by %).

Origin		Gender	
Non-Papua Indonesian	34	Male	82
Highland Papuan	54	Female	18
Coastal Papuan	6		
Western	6		

Table 3. System Costs Under Shared Infrastructure and Nonshared Infrastructure Models.

Item	Shared (in $)	Nonshared (in $)	Frequency
BTS RF equipment	$5,400	$5,400	One time
BTS CPU	$100	$100	One time
VSAT equipment	$500	$5,500	One time
Power	$2,750	$4,000	One time
Cabling	$150	$150	One time
Enclosures	$100	$100	One time
Other components	$650	$650	One time
VSAT service	$15	$130	Per month
Maintenance	$100	$100	Per month
Phone number	$0.65	$0.65	Per number-month
Outgoing SMS	$0.01	$0.01	Per message
SIM card	$0.65	$0.65	Per card

Note: The largest capital expenditure is the radio equipment, and the largest operational expenditure is the monthly cost of VSAT service for backhaul. The total upfront cost of the installation is $9,650 when sharing infrastructure, $15,900 when not.

only option—our usage results show that out-of-network communications are the most valuable to users in Desa. We also faced particularly high recurring monthly costs for phone numbers because we bought numbers at retail prices rather than on the wholesale market. Because of this, WamenaCom requires users to prepay one year's worth of charges for their number. This ensures that we do not operate at a loss. Users have begun renewing their numbers to continue service.

On the revenue side (Table 4), the highest grossing service was out-of-network SMS, accounting for 84% of total revenue. Calls accounted for less than 2%, and the remaining 13% of revenue came from local SMS. In 16 months of operation, the system grossed $15,634.21 for the local community, or approximately $977.14 per month. Our distribution of revenue per user is shown in Figure 6. Our median user spent $0.94 per month. Together, the top 10% of users accounted for 48.8% of revenue. Our average revenue per user per month (ARPU) was $2.74, compared to the ARPU for prepaid users of the largest Indonesian carrier Telkomsel of $3.60 (Telkomsel, 2012). The ARPU is probably understated, as we overcount subscribers who are no longer active users.

Table 5 presents our projected monthly profit for the network under a variety of growth rates. Our model uses actual network revenues and costs for the first 16 months. For subsequent months, the projection assumes that the current average monthly cash flow will remain constant (i.e., usage patterns do not change) and that each new user will generate the current median monthly cash flow per user of $0.94. We further assume that capital costs will be financed by a five-year loan at 12.4% APR (World Bank, 2012), paid monthly. Thus, the analysis allows for a complete system replacement (including BTS, solar equipment, batteries, and VSAT) every five years. The system's current monthly profit using these assumptions is $374.21 and $72.33

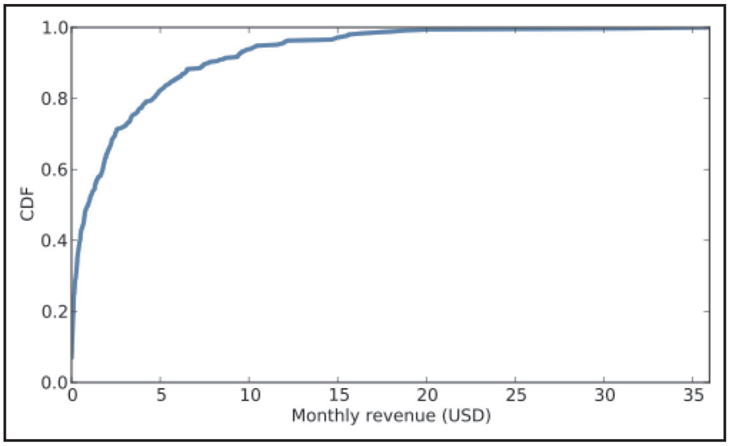

Figure 6. CDF of revenue per user per month. While 50% of users spent less than $0.94 per month, they accounted for 4.5% of total monthly revenue; the top 10% of users accounted for more than 49% of monthly revenue. Many subscribers have gone completely inactive, exaggerating these results.

under the shared and nonshared models, respectively. Note that these are slightly higher than our earlier results (Heimerl et al., 2013).

Our profit estimates, combined with the system's ARPU, are key results. Local cellular networks have latitude to set prices appropriate to the costs of serving their area. In contrast, incumbent national providers must set prices uniformly across all users and compete on a large scale. For example, Telkomsel charges 150 rupiah per SMS to Indonesia, while our partners charge 900.[2] These prices put the system just above the break-even point under the nonshared infrastructure model. Meanwhile, the ability to share common infrastructure (as we share power and backhaul connectivity

Table 4. Number of Usages of Each Service Type for the Period February 11, 2013–August 12, 2014.

Usage Type	Amount	Revenue (in $)
Outside SMS	143,546	$13,135.02
Incoming SMS	130,606	—
Local SMS	104,445	$2,142.89
Free SMS	48,772	—
Local Call	45,432	$318.54
Free Call	11,444	—
Credit Transfer	7,383	—
Total	574,395	$15,634.21

Note: Revenue shown is for the network operator and does not include reseller revenue.

Table 5. Projected Mean Monthly Profit over 5 Years.

Growth Rate	Shared (in $)	Nonshared (in $)
0 users/month	$374.21	$72.33
5 users/month	$384.74	$82.86
10 users/month	$401.16	$99.28

Note: Future estimates are slightly lower than our earlier work (Heimerl et al., 2013) primarily because of the reduced median revenue per user.

2. This may seem high, but other goods in Desa are similarly expensive: 1kg of sugar is 25,000 rupiah (vs. 8,000 in Jayapura), 1kg of rice is 20,000 rupiah (vs. 5,000), and 1kg chicken is 65,000 rupiah (vs. 14,000).

Table 6. Income for Credit Resellers (in $) for the First Six Months of Operation. Secondary 1 began sales on March 25, 2013 and Secondary 2 on April 3, 2013

	Primary	Secondary 1	Secondary 2
Amount Sold	$3,955.93	$987.07	$2,852.12
Cost	$3,955.93	$1,091.95	$2,932.45
Revenue	$4,177.24	$1,177.45	$3,303.93
Avg. Markup	5.6%	19.3%	15.8%
Profit/Month	$36.48	$18.19	$85.07
Sales/Month	9.7	71.1	290.4

with our local partner) substantially reduces costs, particularly capital expenditures. As a result, shared infrastructure networks are able to take advantage of the lower cost to operate more profitably in rural environments such as Desa.

Last, although covering the first six months of operation, we note that the network is profitable for the local resellers (Table 6). It is hard to gauge the relative impact of these funds on the sellers. However, as each seller conducts numerous transactions every day, it is likely a valuable income source.

Interviews

Throughout the deployment, we conducted numerous design discussions with users. We also conducted formal interviews with six users in Desa and a group of three people in Jayapura, the capital of the Province of Papua, who were in contact with users in Desa. One of the interviewees in Jayapura is a resident of Desa. The formal interview targets were indigenous Papuans, comprising five males and four females. Ages ranged widely, with two interviewees being students at the local government school (not MS), two being older church organizers, and the remaining five being adults. The interviews were done in Bahasa Indonesia and translated by a fluent speaker on our team, who also conducted the interviews. We first note the uptake of the service:

Interviewer: Among your friends in Desa, are many people using cards?

Garet: Oohhhh! Lots! You can see for yourself, right? Later, you can ask Matias. He is the one who sells [credits]. There are already so many customers. The other day I saw the list, there are almost . . . 200 there. From the villages they also want to come buy.

We also sought to answer key questions about our intervention:

- How did the intervention benefit you and/or the community?
- How was the network used?
- What problems have you seen, or expect to see?
- What's your perspective on who owns the network?

Benefits

The one message that permeated eight of the nine interviews was the value the network brought to the community. Users would make sure to mention their appreciation of the network and how important it is:

Benjamin: We are here as customers of WamenaCom, here in Distrik Desa. We are very grateful for the installation of the WamenaCom network. This is a very big change, an extraordinary change. It can build communication for these two districts. So I now say thank you just for this.

Garet: People have been coming and saying, "Desa has a special network." So we are proud. This is one of the things that can bring us to be . . . advanced. Not like others. Others use Telkomsel; we have a different network. This is what I was thinking. I felt very happy. So I was thinking, "I don't have to go to

Wamena anymore to send SMS, to phone in Wamena." I can relax here in Desa, sitting in the forest, roasting cassava.

Paulus: So generally people are happiest because now they know that Desa already has a network [that works]. So they can SMS to family in Desa, from there they can SMS to Jakarta, to anywhere, because Desa kids, many of them are taking studies in Jakarta, in Sentani here, in Manado, in Jogja. So parents are happy, because, right away, if one needs anything one simply contacts one's parents by SMS. So they are happy.

Use

Communication with family was very important. Every interviewee in Desa listed it as a primary use of the network. Leaving one's home village for opportunities elsewhere is routine in Papua. Similarly, many non-Papuan Indonesians from nearby islands travel to Papua for work, including military service. These migrations, combined with strong familial bonds, led to this desire among our interviewees:

Garet: At the time of the [large social gathering], I already got my card. I sent SMSs, but I didn't send here, because I miss my family over there, I try sending SMS over there, and . . . to Wamena. So, I try like this, and—eh!—smooth!

Selina: With the younger sibling in Jayapura, as it happens she is now studying. So, she is still studying, and she is also in her final semester . . . We checked the developments, how is it, after long in Wamena. Maybe is she sick, or what, tired. We asked like this, and are there any shortages or not. We checked so we can complete her needs. That's why we checked with the family that is over there.

Surprisingly, there was no discussion of business use of the network. This is likely a consequence of only interviewing Papuans, who own very little of Desa's commercial infrastructure. Instead, two interviewees used it for local politics. For example:

Selina: [An important politician] is my older male relative, so I follow developments: "How are things going?" and so on. If there are obstacles, challenges, we can support in prayer, so it is smooth.

Lastly, in-network communications were surprisingly common; two interviewees used them to organize village activities. This was unexpected, given Desa's relatively small size. As one of the youths noted:

Interviewer: Why do you send SMS within Desa, even if it's close? You could speak directly, but you send SMS. What is the purpose?

Letty: Well maybe, for example, I'm at home and I SMS a friend or contact them, say, "Hey! Please come pick me up, ok?" So we can go walking around.

Problems

Although local communications no doubt benefited the youth; others in the community were less optimistic about these messages. Two of the interviewees in Desa and one in Jayapura expressed concern about the youth dating and the network's role in that:

Benjamin: People say having a network is a big change. Some older people say it is not so good. This difference between good and that bad or negative, the issue is that someone who already has a [cellphone] and has purchased this WamenaCom card, maybe they can send SMS like "OK, how about we meet up" and so on with girlfriends or boyfriends.

and

Selina: But on the negative side, meaning, but even that, it all depends and returns to us. We parents, especially we parents who have sons and daughters who are teenagers, who all this time maybe have been under tight supervision by their parents, but now with WamenaCom being here, yes, maybe parents are not watching closely, and children pull.

We note that this concern isn't about WamenaCom in particular, but rather an apprehension about mobile phones in general. Nor is it paranoia; some of our other interview targets spoke about contacting potential or existing romantic partners.

We also note that a few users mentioned technical issues. One of the students was unable to communicate with anyone in Wamena for some unknown reason, and this user was the only one to not speak highly of the network. There was also an issue one interviewee brought up concerning how users outside of the network understood our numbers and sometimes confused them with spam:

Garet: I call my brother. So for instance I needed money, so I had to go through, communicate with them. But they didn't believe, because only SMS, even though I already gave them the number clearly and my identity clearly, so I went straight there, so then they believed.

Ownership

As our network is nontraditional, we were curious about how users viewed the network ownership. As the researchers spent months in the field and interacted with the Desa population, we were well-known. As one person noted:

Garet: Well [one local person] said, "The one who owns this network, is from . . . over there. There is this guy who left already, right?

Interviewer: Kurtis?

Garet: Right.

Two other interviewees attributed ownership to the NGO that housed the equipment, *Misionaris Sekolahin,* and its leader, Regis.

Interviewer: [Who owns the network?]

Selina: All we know is, it's through Uncle Regis. Through Regis, so . . . we are sure, because Regis is here, he is here together with us always, so we are sure, this is through Regis, so we believe, and we buy that card.

and

Paulus: Indeed, that day, I asked Garet, and he said, "Mr. Regis made this." He said that, Mr. Regis made it, not Telkomsel.

Lastly, one of the interviewees seemingly believed that the community owned the network:

Herman: Well according to me, this network, indeed, those who installed it, I don't really know, but it helps, so it's public.

Interviewer: Public, owned by the public?

Herman: Yes, it belongs to the public. Because at this time it is in Desa, so I think . . . people there use it, so it's publicly owned.

Discussion

Local Implications

Although we describe our system as local, we emphasize that it is not run by indigenous people. Both operating organizations, WC and MS, are run by non-Papuans. WC is run by an American technologist in Wamena. MS is run by an American couple who have lived in Papua for more than a decade. We describe our project as "local" because the tower is located within the community and operated by community members. Similarly, the operators are "locals," based on their long-term presence in, involvement in, and knowledge of Desa.

Being local does not mean the technology or intervention will always benefit the community. Far from it—

even "local" agents may be as destructive as any other. For example, this system was deployed in partnership with an existing Papuan-run Christian mission. The long colonial history of Christian missions in Papua should not be ignored. Part of our work reinforces existing colonial power structures, potentially at the expense of indigenous ones. Although we strongly believe in the good intentions of our missionary partners, this arrangement could cause harm. Our goal in this work is to make cellular systems more accessible from a cost and technology perspective. Our belief is that this will enable more local, community-based actors to provide connectivity. Eventually, any group with sufficient will and a small amount of start-up capital will be able to run its own network, including groups with fewer resources and organizational capacity than WC and MS.

Policy Support

Our network runs without a spectrum license. This is an enormous risk to the project and the operators, and one not taken lightly. Though it has been fairly successful in this particular instance, we wish to reiterate that network operators should always ensure they have all the necessary permits and regulatory approval before operating in licensed spectrum bands.

Substantive policy changes could reduce this risk for rural entrants and encourage innovation in small-scale telephony networks. We hope that our work, showing meaningful gains for rural users from local cellular networks, will positively benefit ongoing spectrum licensing reform movements. One approach is that of the Netherlands, which has set aside a portion of the DCS1800 band for unlicensed, low-power GSM networks (Agentschap Telecom, 2013). More useful for rural areas would be setting aside the first five channels (ARFCNs) of the GSM900 band (less than 5% of that band) for unlicensed, small-scale networks operating outside existing coverage areas.

As a potential solution, we have proposed an alternative technology and policy framework for sharing GSM spectrum called GSM White Space (Hasan et al., 2014). This technology allows multiple networks to interoperate in the same frequencies without interference, while employing existing 2G GSM phones. We believe GSMWS is best suited for rural areas where spectrum is lightly used but highly regulated and would allow small-scale local entrepreneurs to legally bring coverage to their own communities.

Similarly, the relatively low margins of small-scale cellular networks make them particularly sensitive to high interconnection fees, which incumbent providers use to price out new competitors. Another (perhaps unintentional) barrier to entry for small operators is zealous blocking of SMS by incumbent providers to reduce spam. Opaque blocking criteria and the difficulty of communicating with incumbent providers compound this issue. Regulation to ensure fair interconnection with incumbent providers would be a major benefit for rural operators. These regulations exist in the United States, and are a key reason for its relatively high number of rural operators.

Generalizability

Papua is a unique place in the world; there are few places with so many geographical obstacles to infrastructure development, so much natural wealth, and such wide cultural diversity. Because of this, we cannot know if our results will generalize to other parts of the world. The specific technologies (e.g., VSAT, wifi, hydro, solar) and specific social and technological structures (e.g., prepaid, prices, credit selling) used will no doubt depend on factors related to the target location. However, our design is based on a fundamental principle that does generalize: empowering local agents to solve their own communication problems with the materials and knowledge available in their community. For this reason, we believe our designs and technology will work in other areas and we plan to demonstrate that in future work.

Alternative Models of Local Ownership

Our deployment, being only one at present, follows a simple model of local ownership; our partner organizations are led by individual immigrants to Papua. These leaders control the organizations completely; other members are employees or customers. Although this signals a limitation of our study, we believe our system could work with other organizational structures as well, such as cooperatives or franchisees. Grameen Telecom (Alam, Yusuf, & Coghill, 2009) used a franchisee model, but their "phone ladies" only had to buy phones and not base stations. Our franchisees would need more capital and technical capacity, but would also extend coverage (unlike Grameen).

Cellular networks, like many other types of infrastructure, are vital to the whole community. In Desa, we have 349 customers. We envision an alternative model: a cooperative network (Galperin & Bar, 2006) where each member both owns and pays into the system. Rhizomatica (n.d.) is an example: it is a community-owned OpenBTS-based network in Mexico. We envision services in the network that would support this vision of participatory governance; for example, SMS voting and broadcasting community meet-ups. Our work is only a first step that demonstrates the feasibility of small-scale local cellular networks. We will continue to explore how to support other ownership models as we move forward.

Conclusion

Cellular networks cross the globe, covering billions of people. However, other hundreds of millions still lack coverage. At least part of the reason is structural: Traditional cellular networks are built top-down, driven by the profit motive of large carriers or by political pressures from governments. Areas that are less profitable or lack powerful politicians are often left without communications services.

In this work, we proposed an alternative model for cellular systems: building them bottom-up, with local people installing and operating small-scale, sustainable telecommunications firms, leveraging local infrastructure when available. We evaluated this model by building and deploying a system in rural Papua, Indonesia in partnership with two local NGOs. We showed that such a system can generate a profit for local operators in a sustainable way and benefit the community by bringing important telecommunications to areas that lack them. It is our belief that this bottom-up model can bring cellular connectivity to those without coverage in ways that are sustainable and profitable for local communities. ■

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