Experiences: Design, Implementation, and Deployment of CoLTE, a Community LTE Solution

Spencer Sevilla, Matthew Johnson, Pat Kosakanchit, Jenny Liang, Kurtis Heimerl
{sevilla,matt9j,pathik,jliang9,kheimerl}@cs.washington.edu
Paul G. Allen School of Computer Science and Engineering
University of Washington, Seattle, WA

ABSTRACT

In this paper we introduce CoLTE, a solution for LTE-based community networks. CoLTE is a lightweight, Internet-only LTE core network (EPC) designed to facilitate the deployment and operation of small-scale, community owned and operated LTE networks in rural areas with limited and unreliable backhaul. The key differentiator of CoLTE, when compared to existing LTE solutions, is that in CoLTE the EPC is designed to be located in the field and deployed alongside a small number of cellular radios (eNodeBs), as opposed to the centralized model seen in large-scale telecom networks. We also provide performance results and lessons learned from a real-world CoLTE network deployed in rural Indonesia. This network has been sustainably operating for over six months, currently serves over 40 active users, and provides measured backhaul reductions of up to 45% when compared to cloud-core solutions.

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1 INTRODUCTION

The Internet recently passed the four billion user mark [1]. Despite this massive accomplishment, growth is rapidly slowing as dense, urban markets become saturated with cellular broadband signals. As the GSM Association noted in 2016:

Figure 1: Tower installed on the local school's roof, reusing existing infrastructure. This CoLTE site is able to cover the entire community from a single location.

"In most countries, even in Africa, mobile operators have already rolled out 2G and 3G network coverage as far as possible within the envelope of a commercially sustainable business model." [2] Similarly, LTE rollouts will slow down as operators shift their focus to metropolitan 5G. This slowing leaves literally over three billion people, primarily in rural and developing regions, without broadband Internet access. The reasons for this are myriad, touching on low population density and socioeconomic status, high install cost, and lack of existing infrastructure.

Affordably providing broadband Internet to this long tail of rural communities worldwide is an open research challenge. One particularly promising solution is *Community Networking*. Community Networks, largely defined as networks built and operated by local actors in a community-centric and often cooperative fashion, mitigate many of the economic concerns of operating in rural areas. The high cost of rural installations is reduced with local "know-how," skills, and infrastructure. The low density of subscribers is mitigated by strong community participation, often engaging with core "anchor tenants," such as local governments and schools, to ensure long-term sustainability.

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In this work, we focus specifically on community *cellular* networks (CCNs). These networks are particularly well suited to rural and developing areas due to their wide-area coverage, centralized repair and failure structure, and support for low-end handsets. There exist numerous examples of successful CCNs in the world, most notably Rhizomatica [3] (2G GSM) in Mexico, CoCoMoNets [4] (2G GSM) in the Philippines, and Tucan3G (3G UMTS) in Peru [5].

Despite their advantages, the limitations of existing cellular technologies in these contexts are becoming apparent. First and foremost, both 2G and 3G rely on a variety of cellular primitives, including phone numbers and interconnection agreements, that require interoperating with incumbent carriers [6]. Additionally, CCNs operate in licensed bands that are often inaccessible to small organizations. Lastly, they provide only limited connectivity over voice, SMS, and low-bandwidth circuit-switched IP.

In this work we propose, implement, and deploy CoLTE: an LTE-based community networking solution. CoLTE is motivated by our belief that LTE is uniquely well suited to community networking for many reasons: it is wide-area, inexpensive, high-bandwidth, can use IP primitives that remove the need for telecom interconnect, and has recently developed a robust uptake of client devices even in remote areas [7]. LTE is also available in over forty different bands, a number of which are unlicensed or available to small operators.

Despite these advantages, LTE is still fundamentally a telecom technology, designed for highly centralized operation wherein the cellular radios (eNodeBs) are managed by a set of specialized network functions kept in a single location under the operator's control. In cell networks these functions are commonly referred to as the "core," and in LTE as the Enhanced Packet Core (EPC). To resolve this and other constraints, CoLTE reimagines and optimizes the LTE core network towards rural operation in a number of ways. These optimizations include 1) an on-site EPC colocated with the radio access network (RAN) to reduce backhaul costs, 2) support for only over-the-top (OTT) telephony to remove the need for phone numbers and telecom interconnect, 3) all IP-based billing and local services (including support for zero-rating), and 4) leveraging LTE SIM-based auth primitives for network and service authentication, removing the need for passwords in local services.

To evaluate CoLTE, we deployed our system in the rural community of Pagi[1] in remote Papua, Indonesia over a period of six months. This network is operated by a local NGO, sustainably provides broadband Internet access to a community with only existing 2G voice and SMS coverage (no GPRS), and currently connects over forty users to the Internet. We examine the system and show that our design decisions 1) reduced the network backhaul requirements, 2) scale gracefully as more users enter the system, 3) allow for communication through common services like WhatsApp, and 4) do so in an economically viable manner that recoups all operational and capital costs. We have released the entire CoLTE system as a fully open source project [8], and maintain `.deb` packages for Debian 9 and Ubuntu 18.04 LTS.

[1]Name changed for anonymization

Figure 2: Community-Oriented SIM Cards

2 RELATED WORK

Rural Access Networks: Work focusing on bridging the "digital divide" by targeting rural access goes back at least ten years. Surana et al. [9] identified the wide range of challenges faced by wireless networks in rural contexts, focusing on issues ranging from physical component failure and unclean power to disk fragmentation. Designing protocols better suited for these contexts has been one area of focus, with Patra et al. [10] focusing on long-distance wifi and Bandyopadhyay et al [11] and Gardner-Stephen et al. [12] focused on mesh protocols and systems. There are also numerous mesh deployment works [13–16]. Researchers have also focused on systems for these environments, including Johnson et al. [17] developing tools for sharing media, Raza et al. [18] building caching tools, and a variety of groups focused on platforms for service distribution [19, 20].

Traditional Telecom Architecture: Standard cellular network architecture (from GSM to the present) is comprised of a large number of radio base stations (BTS in GSM, eNodeB/eNB in LTE) connected to and controlled by a centralized core network (BSC in GSM, EPC in LTE). Over the past decade, as cloud-based infrastructure has emerged and matured, many works [21–26] have proposed re-architecting the core network into cloud-native software components. This model was developed as a business service by many eNB manufacturers [27–30], and Facebook has recently open-sourced a similarly-architected codebase [31]. More recently, other eNB providers [32, 33] have taken this concept a step further, and now offer cloud-based eNB configuration services alongside a cloud-based network core, with the intent of supporting fully plug-and-play field installations. To persist across short-term backhaul interruptions, [34] combines a cloud EPC with a "smart" eNB at the edge that caches basic EPC functionality and data. CoLTE is different from these designs by locating the EPC entirely at the network edge. Moradi et al. [35] introduces an edge-optimized EPC to support UAV networks, very similar to our colocated EPC but optimized for a different domain (in-network communication with rapid mobility).

Community Networking: Researchers have also focused on the development and deployment of *community networks*, networks owned and operated by local actors and often held in common ownership. Researchers have shown that community networks have the potential to empower local communities [36] and increase resilience [37]. Guifi.net is the largest community network in the world [16, 38], operating in Spain with over 30000 nodes. Many other examples exist throughout the world, including South Africa [13], Thailand [39], India [37], and Argentina [40]. Community networks most commonly use 802.11 WiFi protocols, increasing their accessibility and deployability at the cost of more difficult scaling and repair [6]. We provide a much more thorough comparison with WiFi networks in Section 8.5.

Work by Heimerl et. al. [41–43] and others [3, 5, 44] expanded the community networking space to include small-scale cellular networks that serve up to hundreds of subscribers. More recent work by Hasan et. al. [6] scaled these networks to support thousands of customers in the Philippines by partnering with a national-scale telecom operator. These systems are powerful tools for connecting rural users because of (1) the range and power-efficiency afforded by the 2G waveform and (2) the social impact of voice and SMS. CoLTE is similar to these works, but focuses on broadband Internet service via LTE, as opposed to voice and SMS service via 2G.

3 RURAL NETWORK CONSTRAINTS

Most infrastructure development is focused on dense, urban areas where power, backhaul, and support are readily available. In contrast, we focus our work on relatively small communities (1000 or fewer residents) in remote, hard to reach locations; hundreds of millions of people live in such communities around the world. In this section, we describe the constraints present in these contexts that inform the design of CoLTE.

Limited Infrastructure: Many presently disconnected areas have constrained infrastructure, such as intermittent and/or dirty power [9] or scarce building supplies. These challenges impede conventional telecom rollouts, which deploy one-size-fits-all solutions designed for rapid scalability, because these solutions cannot leverage local context and flexibility. In contrast, community network operators are also community members and intuitively understand how to adapt within the local context to navigate issues such as transportation, power, and easements.

Remote and rural areas also often lack highly-available, high-speed Internet backhaul infrastructure, and typically rely on satellite or long-distance microwave links. The characteristics of these links, particularly highly-variant latency and downtime with weather, are problematic as more and more user-facing Internet and Web services are built for high-bandwidth, low-latency, and always-on contexts. As these services become more centralized and cloud-native, they often implicitly enforce these requirements, even when they are not strictly necessary, via protocol-level design decisions such as overly chatty protocols, short timeout values, and system-level failure in the face of client disconnection.

Low Density & Budget: By definition, rural areas have lower population density than urban areas. At the same time, infrastructural costs are often higher, as equipment and labor must be brought from nearby urban centers. Since economically sustainable rural networks must amortize higher costs across fewer and often less wealthy users, it follows that inexpensive deployment and operation are critical requirements. Increasing the coverage area of the equipment is a natural goal, as is designing systems that are durable, repairable, and low cost. These financial realities limit the feasibility of custom solutions and one-off protocols, since rural-only solutions lose the economies of scale and technical ecosystem that exist with widely-deployed urban standards.

Scale Mismatches: When local organizations take up the mantle of connectivity and implement their own solutions, these solutions will inherently be small-scale and local. This creates problems when using technologies and protocols designed for global-scale communications. In legacy 2G and 3G community cellular networks, a remarkable amount of system complexity was introduced specifically by the need to support interconnect with existing telephony networks. The earliest instances of these networks [42, 44] did not interconnect with existing phone networks at all, and provided only in-network communication. Later instances of these networks provided interconnect via a wide range of designs, including (1) purchasing Swedish numbers via Twilio [43], (2) building a custom system that assigns every subscriber an extension to a single public phone number [3],[2] or (3) building a large, cloud-based system in partnership with a national scale telecom [6]. Unfortunately, each of these solutions comes paired with significant drawbacks: purchasing Twilio numbers immediately became the dominant operating expense of the network, number sharing with extensions does not allow SMS messages into the community, and partnering

[2]This solution can be considered a novel form of "phone number NAT"

with an existing telecom company required a tremendous and complex engineering and organizational effort.

Local Customization: In a less technical sense, community networks are owned and operated locally, and have the need to be customized to meet local development, sustainability, or social goals [19, 20, 45, 46]. Traditional centralized telecom architectures prohibit this customization as most services and configuration are placed at the core. Innovations such as fog computing [47] bring compute closer to the user, but not necessarily within their administrative control, and still disallow development and deployment of local network services.

TV White Space: TV White Space (TVWS) networks [48] deserve special attention in this section, because TVWS protocols are designed, and frequencies chosen, specifically towards expanding rural access. Rather than traditional conflict-mitigation techniques such as relying on broad-area licenses (cellular) or channel-sensing (WiFi), TVWS radios use a globally maintained geo-location database [49] to enable collision-free communication in wide-area bands and transmit powers without requiring operators to possess a license.

The primary drawback of TVWS today is that it is not an access network technology. TVWS networks require the installation of relatively expensive consumer premises equipment (CPE) on each subscriber's house; users then connect to these CPEs over WiFi. This requirement dramatically increases the equipment costs of scaling the network when compared to directly building a wide-area access network,[3] and also provides much less coverage, assuming that customers can connect only to the WiFi AP provided by their CPE. In contrast, LTE is supported by user devices that can connect directly to the base station; this both removes the need for CPE installs while providing "blanket" coverage over the entire area. Finally, the fact that TVWS is not an access technology means that TVWS can be considered orthogonal to our LTE-based solution: a CoLTE network can easily be backhauled to the Internet by TVWS.

4 DESIGN

Our design seeks to enable community cellular networks while addressing the constraints of remote contexts through a novel integration of cellular (3GPP) and IP networking technologies, a non-traditional allocation of physical network resources, and the removal of unnecessary complexity to ease network deployment and customization. We accomplish this by embracing three core ideas: "dumb pipe" [50] forwarding, edge compute, and LTE authentication.

[3]We discuss equipment costs in Section 6.4

4.1 Embracing the "Dumb Pipe"

In contrast to that of telecom, the relationship and interconnect between two IP networks is orders of magnitude simpler [51, 52]. Basic techniques such as NAT and hole-punching enable address-space scalability, and packet-switched forwarding [53] supports high network utilization and resource scalability. Together, these characteristics enable easy internetworking, which in turn has driven global Internet adoption and scalability. This motivates our system design choice to provide only IP-based connectivity and remove any support for telecom interconnect or mobility.

4.1.1 OTT-Only Networking. By supporting only IP traffic, CoLTE does not interconnect with legacy telecom services like voice and SMS, and bills all traffic equally: as IP traffic that is drawn down from a user's data balance (in the case of usage-based plans) or simply logged (in the case of rate-based plans). In billing all traffic as bytes, CoLTE explicitly makes no distinction between in-network VoIP (i.e. VoLTE), over-the-top VoIP (e.g. WhatsApp), or general Internet traffic.

Our decision to not support voice or SMS stems primarily from feedback that these services are a low priority for our users. In Indonesia, as in many other countries (most famously India), the organizational barriers and confusing billing practices associated with voice interconnect between competing telecom companies have driven explosive adoption of WhatsApp. In contrast to the service offered by the national telecom companies, WhatsApp offers users a single and consistent identity, universal reachability over all IP-based networks, and clearly understood billing practices.[4] When faced with the daunting proposition of negotiating expensive interconnection agreements with Indonesian telecom companies, combined with the reality of near-universal WhatsApp adoption within our target communities, we simply chose to follow our users' lead. This also allows us to operate with *low budget* by avoiding costly numbering and interconnect fees.

Relying on over the top services has the added practical benefit of insulating our local operating partner from the responsibility of securing, safeguarding, and sometimes reporting [54] user traffic. These services provide strong end-to-end encryption since they assume an untrusted public Internet substrate, a feature that is notably absent in traditional voice and SMS.

4.1.2 Application Layer Mobility. While LTE networks traditionally are engineered to support seamless link layer handover of flows within the RAN, CoLTE explicitly does not support mobility between eNodeBs (LTE radio basestations).

[4]Though WhatsApp is free, we refer here to the clear practices around IP network billing, which is either sold at a specific speed (rate-based) or amount of data (usage-based).

While handover efficiency is important when networks are very dense or user mobility occurs at high speed, it also introduces a large amount of complexity into the network. More fundamentally, link layer mobility simply does not *match our scale*.

Additionally, in our context, the practical difference between a link layer reconnection and a handover is minimal. While reconnection breaks existing link layer circuits and drops network-native phone calls, it has little impact on OTT-based telephony applications, which are already engineered for robustness against intermittent packet loss. Additionally, in practice these reconnections are rare, since there exist only a small number of eNodeBs in each community and user mobility typically occurs at walking speed.

4.2 Embracing the Edge

Given that backhaul is so limited in our target context, CoLTE moves everything to the edge, including the LTE "core network" itself. CoLTE colocates the EPC within the community, very close to the eNodeBs and specifically downstream of any constrained backhaul links. This approach is important in the context of rural networks, providing us with the benefits of reliable LTE resource signaling, lower backhaul utilization, and local breakout and services.

4.2.1 Local Core Network. An important consequence of colocating the EPC with the RAN is that the backhaul link is used only for Internet-bound traffic, since local network traffic (i.e. traffic between users or between a user and the EPC) and LTE signalling overhead is kept within the community. Given that our target deployment contexts are backhaul-constrained, it is paramount to use this backhaul link as optimally as possible to mitigate the *limited infrastructure*. In Section 6 we evaluate the network bandwidth savings of colocating the EPC with the RAN, and find that these savings are particularly impactful in low-bandwith scenarios, reaching observed savings of up to 45%. Similarly, since LTE tunnels all user equipment (UE) generated network traffic through the core, in a traditional core network all local traffic ceases during any periods of backhaul disconnectivity. By colocating the EPC with the eNodeB, we minimize the consequences of backhaul interruption and preserve local connectivity regardless of backhaul availability.

4.2.2 Local Breakout and Services. A colocated EPC also gives us a powerful mechanism for supporting local communities. By terminating the UE-EPC tunnel at the access point (i.e. "Local Breakout" [55]), we can route and "zero-rate" (i.e., free [56]) specific traffic flows that are of utility to the community. An obvious extension is to do this for local services that are provided by NGO partners or generated by local community actors, thereby providing *local customization*.

4.3 Embracing LTE Security

Finally, an interesting property of the LTE architecture is that it enforces cryptographic verification of end user devices in the network through its Subscriber Identity Module (SIM). Once authenticated, CoLTE can map each UE to a known IP, and ensure that only this UE generates traffic from its assigned IP. This enforcement prevents IP spoofing in the CoLTE network, and makes the IP address a reliable identity proxy for the user involved with each flow. Using IP addresses as user identities simplifies the implementation of CoLTE and allows reuse of the rich ecosystem of performance optimized IP networking tools, detailed in Section 5.

Basing network management on validated IP addresses also allows for easy customization and extension of the services offered in the network (again supporting *local customization*) with basic web programming skills. User and administrator interaction with the network occurs via a locally hosted web interface. Web technologies allow a flexible and visually pleasing UI when accessed both via smartphone or attached computer, and CoLTE's integration of LTE authentication allows the interface to strongly authenticate users by their access device without typing a username and password into the portal (see Section 5.5), a common complaint with the school's existing WiFi hotspot.

5 COLTE IMPLEMENTATION

CoLTE is comprised of of a set of modifications to, and companion software packages for, OpenAirInterface (OAI) [57]. OAI is an open source, all-in-one software EPC compatible with a wide range of commercial off the shelf (COTS) handsets and eNodeBs. Our primary contributions include hardening OAI to be production ready and capable of handling active user traffic, extending OAI to meet our above design goals, and developing Haulage, our prepaid network administration system that enables usage-based or rate-based billing of IP traffic and network management.

5.1 System Overview

Figure 3 illustrates an example CoLTE system deployed behind a limited backhaul (in this case based on satellite), and contrasts this system to a standard telecom deployment. Notably, the major difference of CoLTE is that the EPC is located on-site and downstream of the constrained backhaul link. This enables CoLTE to provide high-bandwidth local connectivity even when the backhaul is unavailable, and satisfies the goal expressed in Section 4.2. We accomplish this by running the EPC on a small mini-computer housed indoors and connected to both the eNodeBs as well as the constrained backhaul using ethernet.

Aside from the key difference of colocation, CoLTE is built remarkably similar to a standard telecom network. Our

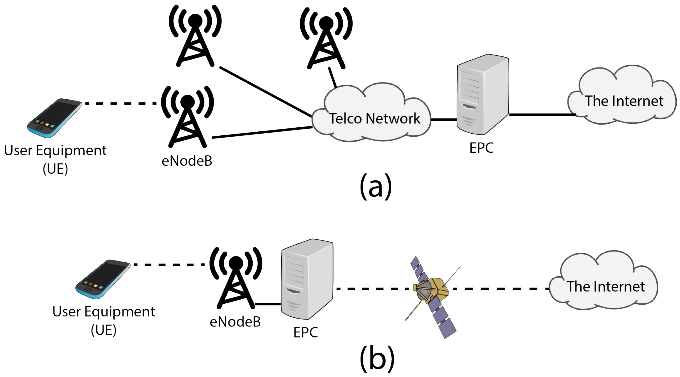

Figure 3: Traditional LTE (a) and CoLTE (b). CoLTE optimizes LTE for operation in remote rural communities poorly served by existing LTE solutions due to their inflexibility and infrastructural requirements.

EPC (HSS, MME, and S/PGW) is fully-functional, stable, and supports the entire set of core LTE protocols (e.g. s6a and s1ap) and identifiers (e.g. IMSIs, TEIDs, and a unique PLMN). This robust and complete engineering effort was needed in order to support COTS eNodeBs at the RAN as well as BYOD handsets for our end-users, as opposed to fixed-wireless CPE. To this point, we also produced and distributed custom SIM cards, illustrated in Figure 2. This approach enables us to provide coverage directly to our users, and also allows us to leverage the LTE security and identity primitives for network management, as described in Section 4.3.

Though our EPC supports the core protocols needed for UE authentication, attach, detach, and mobility, it does *not* currently support two "families" of services commonly provided by LTE: billing and IMS. In standard telecom architecture, the EPC uses a suite of billing protocols (Gx and Gy, among others) to connect to a separate Policy and Charging Rules Function (PCRF) which handles user accounting and authorization. For purposes of simplicity, as well as the reasons enumerated in Section 4.1 ("Embracing the 'Dumb Pipe'") we chose to replace this design with our IP-based accounting manager described in Section 5.3. Similar motivations, as well as the universal adoption of WhatsApp in our target communities, fueled our decision to not support the IP Multimedia Subsystem (IMS), which is used in LTE to handle voice (VoLTE) traffic as well as SMS and MMS messages.

5.2 Extending The OpenAirInterface EPC

The OpenAirInterface codebase was initially designed as a reference implementation for researchers and telecom engineers, and was *not* intended for production systems. As such, our work with OpenAirInterface involved stabilizing the codebase, stress-testing compatibility with different handsets and eNodeBs, building tools to automate and simplify system configuration and orchestration, and writing systems code to ensure that OAI recovers into a running state after a wide range of crashes and/or failures.

5.2.1 Enforcing IP Address Assignment. In LTE, all UE-generated network traffic (both control- and data-plane) is transmitted to the EPC over the GPRS Tunneling Protocol (GTP). CoLTE uses kernel-level GTP encapsulation and deencapsulation via a Linux virtual network interface. Deencapsulation occurs before any routing or filtering decisions are made, and CoLTE explicitly enforces IP address assignment at this point, to ensure that a malicious UE cannot spoof its address.

5.2.2 Default Bearer Traffic. As a part of GTP encapsulation, LTE uses the concept of *bearers* to provide QoS guarantees to specific traffic flows (e.g. VoLTE calls). CoLTE explicitly does *not* utilize this feature of LTE, and instead routes all traffic to/from the UE over the default bearer, which provides only best-effort IP delivery without any QoS. This decision to support only IP traffic via the default bearer channel ties-in with our decisions to not provide network-native support for VoLTE or handover, and to leverage end-to-end principles for simplicity.

5.2.3 Policy-Blind Forwarding. The EPC is traditionally responsible for enforcing a network's administrative and buiness policies, known as the Policy and Charging Control (PCC) System. However, in CoLTE we explicitly separate this logic and functionality into a separate codebase, Haulage. It follows that the EPC is responsible only for establishing and maintaining a radio link and routing/forwarding packets accordingly.

Our decision to divide these functions into separate codebases was driven primarily by engineering considerations. First and foremost, separating Haulage from the EPC allowed rapid development and deployment based on IP primitives and standard Linux kernel interfaces (specifically `iptables`), whereas integration with the EPC would have required a much more complex engineering effort focused on the bearer establishment process. Second, this split enables us to distribute each package separately without introducing any operational codependencies: a CoLTE network without Haulage is simply an unmetered network, and Haulage's reliance on IP primitives means that it can meter non-LTE networks. Finally, this split reflects the standard engineering practice of separating mechanism from policy, and enables each system to evolve independently of the other.

5.3 Haulage PCC

Haulage handles the tracking and enforcement of the operator's business policies in the network. It is divided into three logical functions: a Traffic Detection Function (TDF), a Policy and Charging Rules Function (PCRF), and a Policy and Charging Enforcement Function (PCEF), illustrated in Figure 4. Currently, all three components are deployed as a single userspace program written in Golang; this program runs on the same physical machine as the EPC and lies on the data-plane for all network traffic. Haulage enacts its policies via kernel networking hooks to minimize its impact on latency. This approach minimizes cost while giving the local network operator an environment they are familiar with administering, monitoring, and debugging.

The TDF observes the data-plane of the network, aggregates the bytes used by each user, and reports it to the PCRF after a configurable amount of time or traffic. The TDF captures traffic with `libpcap` and the `gopacket` packet processing framework; this results in sub-optimal packet header duplication but is not a bottleneck in the current implementation. All resources are garbage collected as users leave the network, which allows the TDF to run continuously. Expiration of user update timers or a sufficient number of observed events triggers a callback into the Haulage PCRF.

The PCRF ensures that every user is still in compliance with operator policies and updates the user state in a failure tolerant SQL database for recovery after power outages. Policies are encoded as functions which take current user state as input and output a new desired state, and can contain arbitrary logic like zero-rated services or special promotions. In our current deployment, user state consists of the current data balance, lifetime data used, and whether Internet access is allowed. The policy function generates warnings as the user's balance approaches zero, and updates the user policy with the PCEF to shut off access at zero. The PCRF also accepts updates from the administration and management interfaces to trigger re-enabling access when additional balance has been purchased.

The PCEF enacts policy by installing rules in the appropriate network forwarding appliances (in this deployment, Linux netfilter rules via `iptables`). Since policy enforcement occurs asynchronously to detection and determination, there exists a brief window when a user may have an out of date policy. With the settings in our current deployment, this window is on the order of 10s, and is acceptable to the network operator. Timeout windows can be decreased at the expense of additional calls to the PCRF and higher overhead.

Our main motivation for splitting Haulage into different logical components is to support larger-scale, higher-speed, and mixed-access networks by integrating with existing ISP approaches. For example, many commercial routers and switches support traffic reporting over RADIUS, and could replace the TDF provided by Haulage. Similarly, the PCEF could be extended to enact its policies at SDN-enabled switches via OpenFlow.

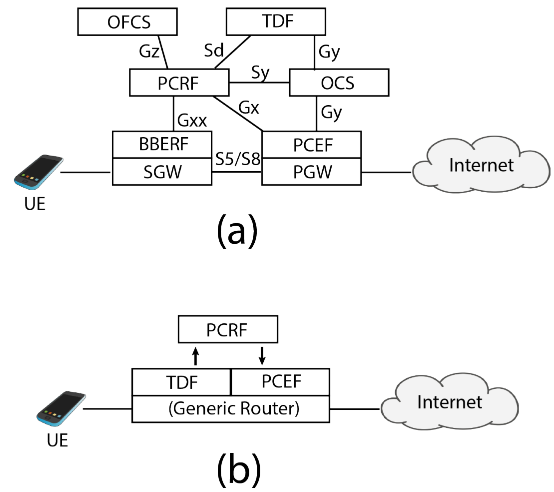

Figure 4: Traditional PCC (a) and Haulage (b)

5.4 IP Address Assignment Interface

As described in Section 5.2.1, the EPC binds IP addresses to UEs and enforces this binding. Subsequently, Haulage uses this IP address to associate packets with a user for purposes of metering and billing. It follows that IP address assignment represents a remarkably nuanced interface in our system, because it is the only point at which the EPC directly interfaces with Haulage.

The need for an interface for IP address assignment between the EPC and Haulage stems from our decision to fully separate the network control and data planes (powered by the EPC) from network management and administration tools (Haulage). This design is unique in the telecom space, which typically enacts all of these functions at the EPC. This design also mimics standard ISP architecture, where network management is split from the protocols responsible for IP assignment (e.g. DHCP or PPPoE).

Initially, this "interface" was simply a shared MySQL database that mapped SIM cards to IP addresses. Understanding the brittleness of this approach, we moved towards a design wherein the EPC interfaced with Haulage using the RADIUS protocol, which is a standard interface for interconnection between ISP management tools and supports push- and pull-based IP assignment. As more and more ISP management software migrates to a REST API approach, we are planning to provide REST support and integration with a wider range of management software.

5.5 IP-Based Service Authentication

Because IP addresses are assigned to the UE by the EPC and verified during GTP deencapsulation, most LTE networks explicitly do not support host-driven protocols for address assignment such as ARP or DHCP. This prevents UEs from learning the IP addresses of other nodes on the network or spoofing their IP address. Additionally, the wireless channel between the UE and the eNodeB is individually encrypted for each user; this prevents channel eavesdropping attacks (e.g. [58]) that are prevalent in WiFi.

CoLTE explicitly assigns UEs the same static IP address when they leave or rejoin the network. When combined with the above two characteristics of LTE, this implies that CoLTE can reliably and securely bind an IP address to a specific SIM. This binding enables us to use IP addresses as user identity primitives, and therefore gives us fine-grained per-user traffic control via standard IP-based tools such as iptables or OpenFlow.

Taking this a step further, we *also* leverage the security of the user-IP binding to provide a novel form of IP-based user identification for our locally hosted services. Rather than relying on usernames and passwords, or building a complex voice- or SMS-based system that relies on telephony primitives, users accessing local webservices are automatically identified via their authenticated IP address. Users then use a simple website hosted on the EPC to perform basic account management operations, such as purchasing data packages or transferring money from one subscriber to another.

6 DEPLOYMENT

In mid-2018, we traveled to the remote Indonesian village of Pagi[5] to deploy the first CoLTE-based rural access network. Deploying our code in a live production setting provided us with invaluable experience, a deep understanding of both the logistical and technical constraints of the area, and helped us situate our work in the community cultural context.

6.1 Local Context

Pagi (pop. ∼1,500) is located outside the Highlands region of Indonesian Papua, at an altitude of approximately 2,000 meters. Pagi is connected to Wamena (pop. 30,000), the major city in the region, via a three-hour truck ride over unpaved roads and one river crossing. Aside from locally-farmed produce (pineapples are a local cash crop), all supplies and infrastructure are transported to Pagi from Wamena.

Pagi largely lacks robust infrastructure. Power in Pagi is provided though diesel gensets scattered throughout the community and by a microgrid consisting of solar panels and a micro hydro-electric generator connected to a battery bank for the large local private school. Power from the hydro is unavailable from 9pm to 6am, varying slightly based on weather, time of year, and event schedules.

[5]Name changed for anonymity.

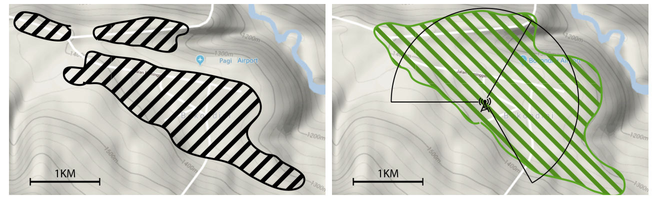

Figure 5: Topo maps of population (left, black) and measured coverage (right, green) in Pagi

The connectivity situation in Pagi is very constrained. In the cellular space, Telkomsel (Indonesia's largest national-scale provider) provides somewhat-irregular[6] 2G service in the community via a single tower. Internet is not available for general consumption. Slow Internet (3 Mbps with a 10:1 contention ratio) is provided by a VSAT satellite connection but available only to teachers for instructional purposes.

Topographically, Pagi exists on a mountainside shelf above a riverbend. To the southwest, a mountainside quickly rises for approximately 1,000 meters; the other directions are bounded by an equally sharp dropoff of approximately 200 meters down to a river. These features essentially define the boundaries of the community, which is illustrated on the left side of Figure 5.

6.2 Deployment Platform

To deploy CoLTE in Pagi, we installed CoLTE and associated services onto an inexpensive Zotac ZBox B Series MiniPC. The ZBox is a mini-PC that comes with a 1.6GHz, 4-Core Intel Celeron processor, 8GB RAM, and a 250GB hard drive. This platform was chosen for cost and ease of replacement, and was literally the cheapest headless PC we could find as of April 2018.

The CoLTE EPC is connected to two 1-watt BaiCells 850MHz Nova-233 eNodeBs with a basic unmanaged gigabit ethernet switch. Each eNodeB radiates to a 120 degree cross polarized (2xMIMO) antenna with 15dBi of gain, with the eNodeBs and antennas configured into the two sectors illustrated on the right side of Figure 5. Note that the "missing" third sector is largely unpopulated and slopes quickly up the aforementioned hill. We use 850 MHz due to a combination of factors, including previously measured handset support [59], long range and coverage, measured spectrum availability, spectrum legality via an experimental license, and the existence of COTS eNodeBs in this band.

We deployed CoLTE with zero-rating and LTE auth for each user's personalized landing page, as shown in Figure 6. This page allowed users to transfer credit and buy data

[6]During our time in Pagi, we heard several reports of (1) voice calls not succeeding and (2) SMS delivered hours after being sent, or dropped entirely.

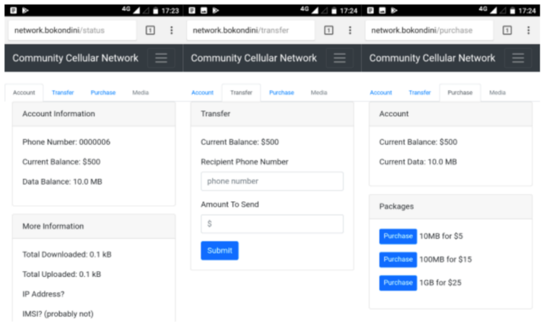

Figure 6: CoLTE landing pages

packages. Our partner asked us to extend this with a localized zero-rated educational media sharing service, which we added as a link from this home page.

6.3 Geographical Coverage

We installed our eNodeBs on a twenty-foot pole mounted on top of the local primary schoolhouse, as illustrated in Figure 1. This location was chosen primarily for logistical considerations, given that the same building also houses the school's electrical infrastructure that we used. This stems from the school's centrality in the community, both geographically and socially, and helped to build community interest in our work.

The exact location of our deployment was sub-optimal from a radio perspective, given the relatively low height of the building and a large amount of surrounding foliage. However, in our field tests we found that the 850 MHz band gave us great penetration and coverage, as illustrated by the coverage map on the right side of Figure 5. Aside from a group of approximately five houses behind a hill in the northwest corner of the maps, our network covers the entire village with relatively strong (-90 dBm) signal, at points reaching distances of over a kilometer from the tower.

Even more remarkably, the borders of coverage were dictated primarily by geography (i.e. the sloping uphill or downhill) rather than signal attenuation. While this observation is clearly anecdotal, it gives us good reason to believe these results will generalize, and implies that our model (which assumes a small set of colocated base stations) is sufficient to cover most small-scale rural communities.

6.4 Expenses

Table 1 provides a breakdown of our total installation cost, which is slightly over 9,000 USD, as well as a breakdown of our monthly system operating expenses.

Note the "0" values for tower construction and monthly power costs and the low value for power infrastructure. These values, which typically dominate the total installation

CAPEX	Cost(USD)
1 EPC	235
2 eNBs	6,800
4 N-Type Cables	155
2 Antennas	536
1,000 SIM Cards	778
Tower Construction	0 (Repurposed)
Power Integration	20
Import Duties	260
Shipping Fees	550
Total Installation	**9334**

OPEX	Cost(USD)
Backhaul	300
Power	0 (School Microgrid)
Maintenance	91
Total Monthly	**391**

Table 1: Capital Expenditures (CAPEX) incurred upfront to construct the site and Operational Expenditures (OPEX) incurred every month for continued operation

and operation costs, are minimized specifically because of our integration with and reuse of preexisting local infrastructure. This highlights a primary strength of the community networking approach; we provide an in-depth example of this strength below.

Power Sharing Example: The standard telecom approach to rural installations with unreliable power is to *provide* reliable power for the tower via off-grid means, typically a diesel generator. This incurs additional installation cost (the generator itself) as well as remarkably high operational costs (purchasing diesel, transporting it to the tower, and guarding it against theft). This likely incurs additional operational and logistical challenges for the telecom company itself, which is far more specialized in supporting telecommunications infrastructure than power infrastructure.

In contrast, we simply engineered our system for resilience in the face of unplanned outages, and then plugged into the community micro-grid. Similar to the above narrative, the availability of this solution to us depended heavily on our relationship with the community, and was only possible as the result of community discussion around power usage. Note that this same community discussion also makes our user-base more sympathetic to power outages: when our network fails due to power interruption, the community is not surprised, because the entire power infrastructure has failed.

6.5 Rollout

We rolled out an initial network launch of 3 users on 21 October, 2018, and added more users in groups of 10 on 31 October, 4 December, 16 January, and 14 February. The timing of these batches was dictated by our need to identify and fix bugs after groups 1, 2, and 3, as well as community timing logistics. The authors are currently gearing up for a "general launch" of the network after this paper is submitted.

6.6 Revenue

The community operator chose to price data at a flat rate of 250 IDR (approximately 0.018 USD) per megabyte, and offers package sizes of 10MB, 100MB, and 200MB [7]. At this rate, our system grosses an average of 27,160,000 IDR (approximately 1,930 USD) per month. This value is clearly well above our operating expenses, and has already sparked community discussion around what should be done with the excess revenue. More broadly, this result makes a strong case for the economic viability of CoLTE installations in similar remote areas, even with a *low budget*. Despite a high price-point by global standards, our network provides immediate utility and value to the community, in no small part by facilitating WhatsApp communication to Wamena. This communication reduces the number of round-trips needed between the villages, which cost 300,000 IDR (21.05 USD) per person and take up an entire day.

7 PERFORMANCE EVALUATION

The deployment of CoLTE in Pagi provided us a unique opportunity to technically evaluate our system in an in situ deployment. In this section, we explore the efficacy of our designs through a variety of metrics including traffic measurements, protocol overhead calculations, and attachment message counts. Our data collection and analysis was conducted in compliance with our University's IRB review process.

7.1 EPC Platform

Network and system observations were taken on our production system in Pagi at 15-minute intervals over the course of two days, with an average of 26.2 attached users over the duration of the evaluation.

System Performance: The CPU and Memory metrics in Table 2 show that the EPC is barely being used. CPU load averaged over 15-minute intervals using `top` reveals that the system hovers around 2%, with peaks of up to 6% utilization during "high-use" hours (i.e. 12:00-14:00 and 17:00-19:00 local time). Similarly, memory utilization for the *entire system*, not just our specific software, stays constant at slightly under 0.7 Gigabytes.

Metric	Value (Mean)
CPU Utilization	2.6%
Memory Use	0.68 GB
Loopback Throughput	14 Gbps
Ethernet Throughput	956 Mbps
USB-Ethernet Throughput	96 Mbps

Table 2: EPC platform system utilization under typical workload and max throughput

Throughput Measurements: The throughput tests in Table 2 illustrate three separate points. First, loopback throughput reveals the maximum packet-processing rate the system can handle in software; this rate (14 Gbps) is higher than expected and exists well above other system bottlenecks (i.e. our 3Mbps backhaul link). Second, throughput across the Ethernet and USB-Ethernet interfaces reveals that total system throughput is defined by the physical limits of the forwarding interfaces (note that the native Ethernet port can forward at approximately 1 Gbps, whereas our USB-Ethernet adapter only supports 100 Mbps).

Implications: This comparison highlights the most significant bottleneck of our deployment platform: it comes with only one native ethernet port. 100 Mbps is likely to remain well above our available backhaul for the foreseeable future, and this problem is easily resolvable by migrating to a miniPC platform with two gigabit Ethernet ports. However, this limit to our system invites an architectural discussion towards the future. In our current network design, the EPC is a gateway that routes/forwards all network traffic, but further separation of the control- and data-planes could enable less constrained designs. For example, both the EPC and Haulage's data-plane operations could be replaced by an SDN application that interfaces with a high-performance router, thereby completely removing CoLTE from the data plane.

We note that fifteen-minute intervals do not capture the bursty nature of network processing and signaling, and throughput tests are not always representative of actual forwarding capacity. However, these metrics still substantiate our claim that EPC functionality can feasibly and affordably be enacted at the edge of the network, particularly when the edge is behind a constrained network link.[8]. This argument becomes even stronger when it is taken into account that we specifically optimized our platform for *cost* rather than computational power.

[7] This rate is more expensive than the Indonesian national average, but we deferred business decisions to our partner

[8] We discuss this further in Section 7.4

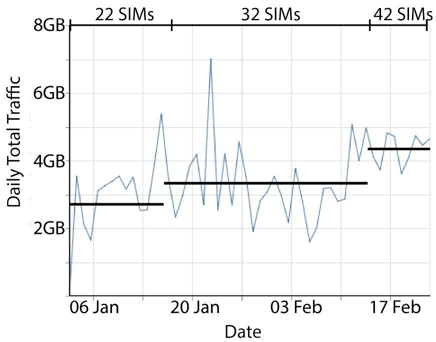

Figure 7: Daily total traffic

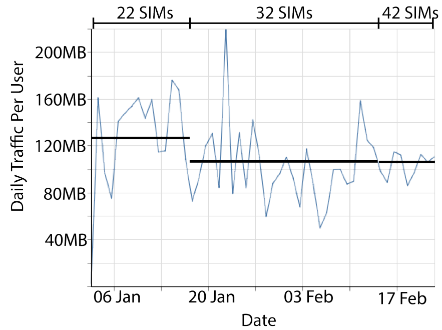

Figure 8: Daily traffic per user

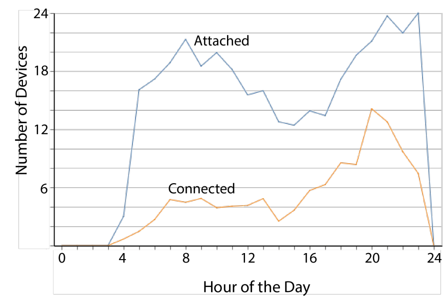

Figure 9: Devices per hour

7.2 Daily Network Usage

Figure 7 provides a graph of total backhaul usage per day, and Figure 8 provides the same graph normalized by the number of users in the system. The means are calculated separately depending on the number of SIMs distributed, noting that they were released in bundles of ten into the community. At the highest level, these figures demonstrate robust usage of the network by the community. They also illustrate that the average usage per-user stays relatively constant, ranging between 104 and 124 megabytes per user per day, while the total bandwidth used per day increases correspondingly. This is surprising to us, as we expected the backhaul to be immediately saturated by even a small number of users. The prospect of over forty active users sharing a low-speed high-contention Internet backhaul opens many usage questions, and requires a much deeper investigation well outside the scope of this paper.

7.3 Daily RAN Attachments

When a user hits a zero balance and is cut off from network access, the user can still attach to our RAN; this is because Haulage enforces access policies at the IP forwarding layer of the EPC. Even though our network is clearly backhaul constrained, this decision invites an evaluation of RAN utilization.

Figure 9 provides a graph, collected over two days, of the hourly mean Connected (actively transmitting) and Attached (including idle) devices. This graph shows standard usage patterns, with zero devices when the network is off. However, this graph also shows us that (1) there exists a large difference between the mean number of attached (19.2) and connected (6.25) devices, and (2) both of these values are well below the total number of SIMs in the system (42). Each eNodeB supports 255 connected users and 150 Mbps of throughput, leading us to believe that our architecture can support many more users (and a backhaul improvement of up to 100x the current rate of 3Mbps) before we encounter resource contention in the fronthaul.

Traffic (Two Day Total)	Amount	Overhead
Total EPC-eNB	8.86GB	-
Total Internet	6.1GB	-
EPC-UE Control Signaling	2.42GB	39.0%
GTP/IP Encapsulation	335MB	5.5%
Total LTE Overhead	**2.76GB**	**44.5%**

Table 3: LTE-Induced Network Overhead

7.4 LTE-Induced Overhead

Table 3 examines the traffic overhead induced by LTE in our network, collected over two days. The top two lines provide raw collected metrics, and the bottom three lines provide a breakdown of the signaling between the EPC and eNB. Overhead is calculated against UE-Internet IP traffic, which would simply be forwarded as-is in a non LTE network.

The breakdown of these results shows that while the data-plane overhead in LTE is relatively low (5.5%), the total network overhead (44.5%) is remarkably high and dominated by the control plane (39%). This result is explained by the relationship between the LTE control plane overhead and our constrained network backhaul. In LTE, control plane traffic is relatively fixed for a given device, because control operations deal primarily with device attach, detach, and mobility. Because control plane operations do not scale with the amount of traffic a device sends, and data-plane traffic does not generate any control-plane communication, it follows that the main variable that dictates the ratio of control plane overhead is the amount of data transmitted by the device. If, for example, our network had 10x the upstream capacity (i.e. a 30 Mbps backhaul serving 61GB of Internet traffic per day, resulting in 3.35GB of GTP overhead) while holding the number of network users (and control plane operations) constant at 2.42GB, the total network overhead would drop

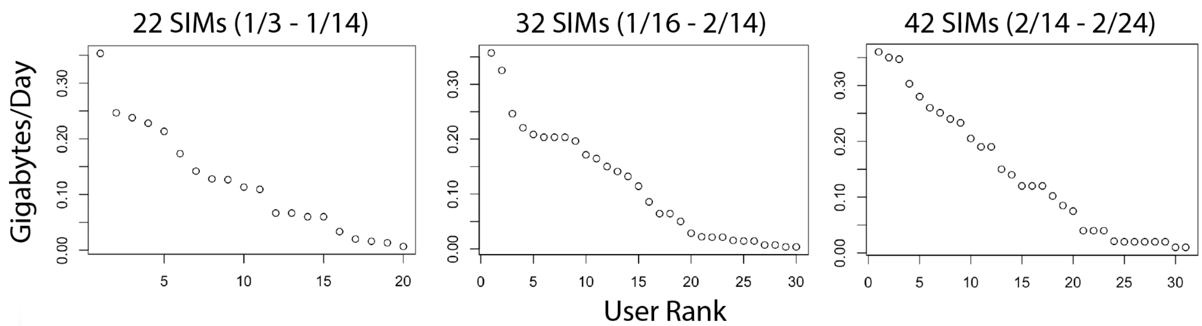

Figure 10: Bandwidth Consumed Per User

to 5.77GB / 61GB = 9%. More remarkably, at this amount of throughput the network overhead starts to be driven by the data-plane overhead induced by GTP encapsulation, rather than the flat control plane overhead that currently dominates our network.

On its own, the observation that flat control-plane signaling dominates network overhead at very low data-rates is intuitive and unremarkable. However, in our network, this observation (1) highlights the implicit network requirements and assumptions made in the protocol design of LTE, and (2) provides important context by contrasting these requirements with the reality of backhaul availability in rural and remote contexts. It is important to stress that our hypothetical 10x improvement is unlikely to be available at an economically feasible price-point in the near- or medium-term future, and yet even this scenario is very conservative by modern standards: 42 users sharing a 30 Mbps link provides an average usage of 0.71 Mbps per user, well below the 4G definition of 20 Mbps down/5 Mbps up.

It follows that while these results are not necessarily applicable to generic LTE networks, they are pertinent to networks with *limited infrastructure*, particularly in the Internet backhaul. These results make a compelling case for EPC colocation and raise serious questions as to the viability of cloud-based EPCs in these environments. Additionally, these results have strong implications for network architecture and design with respect to satellite-backhauled networks, particularly when these networks are used to support an LTE (or 5G) access network.

7.5 Individual Network Usage

Figure 10 illustrates how much total bandwidth each user has consumed, broken into three “Phases” that correspond to the number of users in the network. The single outlier in the first phase (and two outliers in the second phase) are known credit re-sellers who also sell hotspot access off of their phone. We presume that the “shelf" in the second phase represents multiple users sharing a SIM for access. The gradual linear shaping of the curve over time leads us to conclude that as more SIMs enter the network, users (1) normalize their consumption and (2) stop purchasing hotspot access or otherwise sharing SIMs.

Metric	Value	Percent
Bytes Per Day	196MB	4%
Connections Per Day	2126	1.5%

Table 4: WhatsApp Backhaul Traffic

7.6 Telephony Services

We analyzed a week’s worth of network traffic with the goal of quantifying the impact of OTT telecom services. We focused exclusively on WhatsApp due to local knowledge that WhatsApp is by far the most widely used OTT telephony service in the community. The results in Table 4 show that WhatsApp traffic consumes a relatively low amount of total network bandwidth, yet the large number of flows indicates that our OTT-only approach is actively used by the community. The fact that the normalized bytes are larger than the normalized number of connections also implies that our subscribers were making use of higher-bandwidth services such as voice and video calls rather than just text.

8 DISCUSSION

8.1 Field Obervations

Handset Heterogeneity Is A Long Tail: During the network rollout in Section 6.5, our team encountered a wide range of diverse bugs. This can be attributed to the large number of optional header-fields and potentially different code-paths that exist in LTE, as well as widespread heterogeneity in handset models and manufacturers who sometimes implement optional features incorrectly. This heterogeneity continues to be the bottleneck and primary motivation for our team to restrict SIM card distribution as a hedge and triage technique against future bugs.

Hotspots Both Help And Hinder: Almost immediately after our team distributed the initial set of 10 SIM cards, a robust "secondary" hotspot market emerged, with network users selling access to other users. This finding surprised us at first, particularly seeing individual users consume such large amounts of data. However, it simply continues the above-mentioned theme of community members meeting us where we were.

Unfortunately, hotspotted access had the secondary effect of “fuzzing" our understanding of per-user usage patterns, as well as our total network usage as we added users. However, overall, the hotspot market significantly helped alleviate some of the community pressure for SIM distribution, especially since our initial impetus to restrict SIM cards stemmed primarily from handset compatibility issues.

Community Knowledge Drives Analysis: A consistent conclusion of community network analyses is that you must understand the community dynamics at play before you can make sense of the usage data. Our deployment was no exception to this rule. Confusing data-points, such as the massive usage “spike" on 23 Jan in Figure 7 (the mayor celebrating a community event by purchasing and sharing literally 3 GB of data in a single day) or the two heavy users in Phase 2 of Figure 10 (the reseller employing a relative to help him sell data), were explained only by asking the members of the community.

Users Meet Operators Halfway: An important theme we observed in many contexts was that our users sincerely wanted Internet access, and to this point would actively work to meet us where we were. At one point, the team was informed that a specific make of phone was not connecting to our network (see: “handset heterogeneity” above). Within a week (and well before we were able to debug the issue) the complaint disappeared, as the two affected users had simply sold their phones on the used market and purchased a make that was already known to be compatible.[9]

This theme repeats in our users’ adoption of WhatsApp for telecom service and heavy usage of hotspots mentioned above. Additionally, our users have demonstrated an active willingness to contact us (via a variety of means) to report network outages and slow speeds, and have demonstrated remarkable patience with our ability to fix bugs, as well as the network’s limited uptime (62% given the nightly 9pm-6am outages). This resourcefulness and willingness is keenly connected to the community-driven model our network has adpoted, and has been observed in many other rural network contexts [60].

8.2 VoLTE And OTT Services

In comparing network-native voice to OTT services, we note that starting with VoLTE (Voice over LTE), all network-native voice is powered by VoIP and SIP. The true differences between telecom-powered VoLTE and OTT VoIP are twofold. First, VoLTE relies on the network layer to provide security and guarantee specific QoS metrics, whereas OTT services enact both of these tasks at the network endpoints. While certain network optimizations can in fact improve performance, the proliferation of cross-network telephony traffic backhauled by the Internet makes a compelling case for the end-to-end argument [61], which is still understood to be best practice in packet-switched network protocol design.

Second, LTE tags and bills telecom-powered VoIP as minutes, and OTT-powered VoIP as bytes. This difference in billing is astounding: In the United States in October 2018, the median price per gigabyte was 7.02 USD [62] and the cheapest phone plan[10] was 0.10 USD per minute [63]. At this rate, a HD Voice[11] VoLTE call costs approximately 16,000 USD per gigabyte - literally over 2,000 times the median data price, in addition to any roaming or international fees. While VoLTE does provide certain QoS guarantees, this comparison quantifies the user-borne costs of such service.

8.3 An IP Approach to 3GPP Access

Modern (LTE and beyond) telecom systems expose the S2, GX, and SW interfaces for “Trusted Non-3GPP Access.” This interface is designed to allow telecom companies to extend and seamlessly integrate their networks with any generic IP-based access technology, such as WiFi or Ethernet, without sacrificing any of the fine-grained billing or monitoring primitives provided by their PCC.

The “Trusted Non-3GPP Access” interfaces represent an effort to unify telecom and IP networks under a single management and administrative domain. While this unification is appealing, the “Trusted Non-3GPP Access" paradigm turns IP access networks into nothing more than a subset of telecom networks, and necessarily imposes telecom architectural choices on the network, such as QoS-enforced bearer channels, event-based billing, and network-layer security.

This work is part of a continued effort to push back on the wisdom of imposing these legacy telecom architectural primitives on users, especially given that (1) mobile network traffic is increasingly dominated by data, and (2) mobile networks are now built on top of IP networks. In contrast, we firmly believe that the inverse approach is preferable: the architecture and design of future telecom networks should reflect the dominance of these IP primitives and therefore resemble ISP management systems with voice and SMS added as a subset of the network service provided. The architecture of our billing system (and billing decisions) reflects this vision.

[9] Ironically, this trait has made it difficult for us to correctly identify and fix some of the bugs relating to handset heterogeneity.

[10] Excluding unlimited plans

[11] 32 kbps each direction for a total of 64 kbps

8.4 Comparing to Cloud-based EPCs

A variety of researchers and practitioners have been developing cloud based EPCs that could be applicable to rural areas. Examples include BaiCells' CloudCore [32], Echo [24], and Nokia's Kuha [33].[12] These centralized solutions promise easier setup and configuration, potentially a boon for less tech-literate installers.

In practice, these solutions have issues. BaiCells, for instance, extended their platform to include a local EPC (called HaloB) to handle disconnections to the cloud. Our work supports this, showing that on low-bandwidth backhauls, LTE signalling can consume problematic amounts of capacity. Similarly, the commercial solutions are expensive, often charging a substantial per-user monthly fee. Though rural backhaul may eventually improve to support a purely cloud-based solution, it seems likely that local cores will remain the most viable solution for rural areas in the near future. Additionally, CoLTE offers communities flexibility, agency, and system ownership; centralized cloud solutions fundamentally do not provide any of these.

8.5 Comparing to WiFi

Most existing community networks today, including the largest community network on earth [16], are built using 802.11 WiFi technology running static mesh protocols. While these networks are clearly successful in their environments, they also suffer from several key drawbacks, particularly in the more rural environments targeted by this work.

First and foremost, WiFi access points have a greatly reduced range, with omnidirectional antennas covering an average radius of approximately 25 meters, as opposed to over 2 kilometers of measured coverage for our deployment in Pagi. This reduced transmit radius, as well as the less-penetrative nature of the 2.4GHz and 5GHz bands, means that covering an equivalent region requires many, many more access points, typically with a single AP installed per-household.

This large number of APs increases the hardware cost of the deployment and (more importantly) deployment complexity, since each AP must be installed correctly and connected to reliable power and backhaul. Backhaul in these networks is generally provided with additional specialized link hardware, such as point-to-point microwave links or WiFi radios with highly directional antennas. These antennas must be carefully aligned, and are often configured into a static mesh topology, relaying coverage from house to house.

When mesh topologies are employed in rural contexts, the low density of APs in the region often makes them remarkably fragile, non-robust, and bandwidth-constrained. For example, point-to-point links can fail with antenna misalignment of even a few degrees; such misalignment can often be caused in the field by relatively standard weather events [9, 64]. This fragility is a serious problem when considered alongside the higher rates of hardware failure seen in rural networks such as the Village Telco Project [14] and AirJaldi [9]. Additionally, the distributed nature of mesh networks makes it more challenging to identify and repair failed units, especially for a relatively low-tech-literate user population.

In contrast, CoLTE suffers from none of these drawbacks. A single base station is able to cover the entire community, and by leveraging a relatively low frequency band (i.e. 850 MHz) we are able to extend coverage through trees and houses. The centralized nature of employing a single base station dramatically simplifies problem identification and correction, and our use of wide-sector antennas eliminates problems pertaining to point-to-point antenna alignment.

Despite these advantages, WiFi continues to hold one key advantage over cellular: its use of unlicensed frequencies removes the regulatory hurdles associated with an LTE deployment. However, this situation is also changing, in several key ways. The existence of our network, along with others [3, 5, 65], demonstrates that it is in fact feasible for small-scale operators to obtain a cellular license. This can be attributed to the dramatic slowdown of coverage provided by national-scale telecoms as well as an increased interest in rural connectivity demonstrated by regulatory agencies. In some countries, this takes the form of a willingness to provide small-scale operators with traditional licenses, in other countries, this takes the form of the agency standardizing a system for dynamic spectrum access, such as the Citizen's Broadband Radio Service (CBRS) in the United States [66]. Finally, LTE itself has been standardized into unlicensed bands [67, 68], though UE support for these bands is currently restricted to CPE, rather than handsets.

9 CONCLUSION

In this paper we presented CoLTE, a LTE solution designed for rural community networks. CoLTE is a novel LTE architecture and a departure from prior telecom work, specifically in its focus on IP-based network primitives, emphasis on OTT telephony services, and colocation of the EPC with the RAN. Results collected over a six-month deployment in Pagi, Indonesia show that CoLTE is an economically sustainable solution for Internet access in rural and remote environments.

The design constraints and decisions made to build CoLTE are unique in that they blur the traditionally strong lines between telecom and ISP architecture. As such, CoLTE opens the door to a wide range of future work and discussion on the convergence (and divergence) of similar hybrid-architecture networks.

[12]The Kuha project has been discontinued as of June 2019.

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