The Challenges of Scaling WISPs

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ABSTRACT

Wireless ISPs (WISPs) are one of the primary means of delivering broadband Internet access to rural and underserved areas of the world. However, WISP operators often struggle to maintain let alone grow their operations. We set out both to understand what challenges WISP operators face and to develop new approaches to help them in managing their networks. First, we present a study we conducted of operating WISPs to understand what barriers they face. Second, we describe our experiences building and using a software system for WISP management, and a new WISP we have built from the ground up using that system. We found that WISPs appear to reach natural scaling limits, and that despite excitement in the networking community about the promise of Software Defined Networking (SDN) in new environments, more mundane functionality like subscriber management provides much of the actual benefit to WISPs.

Categories and Subject Descriptors

C.2.3 [**Computer Communication Networks**]: Network management

General Terms

Design, Economics, Management

Keywords

Wireless, Rural, Network Operations

1. INTRODUCTION

Over the last few years, connecting the vast globally disconnected population of potential users—the next billion—to the Internet has attracted significant attention both in the research community (e.g. via GAIA) and among large industrial players such as Google and Facebook. Rural users are most difficult to connect due to lower subscriber density making profitable operation challenging. The task of connecting these *last* billions of rural users has been taken up by small Wireless ISPs (WISPs), taking advantage of low-cost wireless equipment to build networks in areas often lacking any other Internet infrastructure. These WISPs are small network operators, leveraging low-cost fixed wireless infrastructure to build their networks.

While Internet access, speeds, and the diversity of applications available via that access has, in densely populated areas around the world, rapidly increased in the past decade, rural access has not improved at the same rate. Speeds delivered by many rural WISPs have not scaled with the increasing bandwidth needs of modern applications; some WISPs we became familiar with in the course of this work have neither substantially increased the bandwidth they deliver to subscribers nor decreased prices in a decade.

In this paper, we set out to understand why this situation exists, drawing on our own experiences and those of others, and to use that understanding to develop new systems to help WISPs operate more effectively. We contribute three insights into the problems faced in developing rural Internet access. First, we describe the context of rural Internet access through two studies of WISPs that we conducted. Second, we detail how assumptions about scaling networks and growing Internet access must be rethought to address the problems that WISPs face. Third, we describe a new software system, Celerate, that we are building to meet the needs of new WISP operators; we have actively been using this system for over a year to manage a new WISP we have built in a rural area of North America.

To calibrate our thinking on rural Internet access in general and WISPs in particular, we conducted two studies on WISPs, collectively representing responses from 83 WISPs operating across North America. We found that North American WISPs ability to succeed was driven largely by financial, regulatory, and business factors, rather than shortcomings in network-level tools.

The results of these studies guide our work. First, our findings suggest that there may be natural limits to the size of rural WISPs, and thus the approach to scaling Internet access for the last billion users will require scaling not merely the size of networks but the number of distinct WISP operators. To do so, we concluded that a new architecture for WISP operation is needed to help these new operators build and manage their networks, thereby lowering the barrier for starting and sustaining a WISP. Second, at the outset of our work, we hypothesized that SDN, in some form, could help WISPs and thus help address the problems of rural Internet access. In concept SDN has much to offer to simplify network management and implement complex network policies, but in practice we found more mundane functionality, such as integrating billing with subscriber data, yields more immediate benefits for WISPs. Thus, our development effort focuses on mundane but ultimately more useful management functionality at the expense of sophisticated but unnecessary SDN functionality.

ACM DEV 2015, December 1–2, 2015, London, United Kingdom.

DOI: http://dx.doi.org/10.1145/2830629.2830637.

To validate our findings and to have a testbed for our work on our new architecture, we built and continue to grow an operational WISP to provide broadband Internet to a rural community and indigenous tribe in North America. We describe our experiences in building the network and how we have leveraged it in testing new approaches to be replicated at WISPs elsewhere. To manage our WISP network, we are building Celerate, an architecture for WISP network management. Our aim is to provide a structure for all aspects of starting, operating, and growing a WISP in rural areas. Some of the components of Celerate build upon conventional SDN designs, while some relate to aspects that are either unique to WISPs or are simply ignored in traditional SDN deployments. Architecturally Celerate differs from many SDN systems in that it makes explicit two additional planes—the management subsystem and the operations subsystem—that are typically viewed as outside the scope of the network's design. These planes are essential to managing many networks, especially WISPs, and by making them explicit we clearly define the ways in which the human operators interact with the system. Our aim is to create a system that meets the needs of small WISPs anywhere in the world, and as such we have incorporated the feedback of numerous WISPs into our designs. Our system is open source and is in the early stages of use beyond our primary deployment in a partner WISP who plans to independently leverage it [7].

2. THE CHALLENGES OF WISPS

In mid-2012 we conducted a systematic survey of WISPs throughout the United States, and in 2014 conducted a more focused but informal survey of WISPs in a specific region in North America. WISPs provide service to millions of subscribers throughout the US. Those who are unfamiliar with the WISP industry are often surprised by its size: over two million subscribers are served by WISPs in the US alone, and in rural areas, WISPs can be the only source of broadband Internet access besides satellite [3]. WISPs have an even larger impact outside the US. Ubiquiti, a leading hardware vendor for WISPs, reports that "the substantial majority of [their] sales occur" outside the US, and sees emerging markets as a major opportunity for their growth [28]. These facts are unsurprising when one considers the fundamental reduction in capital expenditure required to build a wireless ISP network compared to a traditional wired one. Falling costs and rising performance of commodity wireless equipment, driven by the popularity of WiFi, have allowed the industry to grow as availability of unlicensed spectrum has increased globally. Early research from the academic community demonstrated that the same chipsets used in laptops and phones could be used to build long-distance WiFi links [17]; since then, similar technologies have been commercialized and are widely available. Radio equipment for a 50km link providing more than 50Mbps of throughput can be had for under $200, with each radio consuming under 5W.

Despite the importance of WISPs for providing economical broadband service to rural areas, there has been little study by the academic community of the WISP industry. We set out to rectify that situation by answering the following questions: a) what are the demographics of rural WISPs, b) what are the key operational challenges WISPs face, and c) what policy support do WISPs require to effectively provide service?

2.1 Methodology

To investigate the operation and characteristics of WISPs in our initial 2012 study, we developed a web-based survey. The survey consisted of 20 questions covering the size of the WISP and its network, budgeting, network failures, and network management.

Size	1–99	100–499	500–999	1000–4999	> 5000
Number	4	17	14	32	5
Percentile	5.5%	29.2%	48.6%	93.1%	100%

Table 1: WISP size (subscriber base) demographics.

After completing the survey, participants were invited to participate in a follow-up semi-structured phone interview. We had a total of 75 responses to our survey; 13 of those participated in a follow-up interview. Twelve of those interviewed were active WISP operators, and of those ten operated networks in rural areas.

We recruited participants via convenience sampling by distributing announcements on three WISP-focused email lists: the Wireless Internet Service Providers Association's (WISPA) public and members-only lists and the Animal Farm Microwave Users Group (AFMUG) list.[1] The WISPA and AFMUG mailing lists have significant overlap, though the latter focuses primarily on users of a particular manufacturer's equipment (Cambium).

The participation rate is difficult to calculate since the membership lists of each list are private. Based on public archive records, 434 unique users posted to the WISPA mailing list in the two years preceding our study; of course, this only captures active list participants on a single mailing list (though likely the largest of the three we contacted). The AFMUG mailing list claims that "list membership exceeds 450 members." Nevertheless, our respondent pool represents a wide cross-section of the WISP industry. The vast majority of our survey respondents were involved in the day-to-day operation of a WISP. Other respondents had operated WISPs in the past, but now served primarily in a management role, often as a result of growing their company through acquisition.

Our second study, conducted in 2014, was a more informal survey of WISPs in the neighboring regions to our target deployment. We talked to 8 WISPs in the region; for all of these, we directly contacted each and spoke with them about their current operations and their potential interest in using Celerate during development. We did not interview any of these WISPs in our 2012 study, though we have no way of knowing if they participated in the web-based survey component.

2.2 Demographics

The WISPs we surveyed were small, by almost any metric one considers. While only 5% of those surveyed had fewer than 100 customers, half had less than 1000, and almost all of those surveyed had fewer than 5000 customers (Table 1). In terms of traffic load, 40% of WISPs surveyed saw a peak traffic demand of under 100Mbps, and 80% had a peak demand of under 500Mbps.

One of the most consistent and striking characteristics of many of our survey respondents was that they often played multiple roles within their WISP's operations. Most survey respondents reported that they filled a combination of business management, technical management, and marketing roles. This is unsurprising, given almost half of respondents had fewer than 5 employees; 90% had less than 25 employees. For the smallest WISPs we talked to, only one or two people were responsible for the entire operation, though hiring part-time or contract workers for specialized tasks such as tower climbing was common.

2.3 Findings

The goal of this study was to develop an understanding of the technical challenges that impacted WISPs, with the hopes of motivating further research on systems to help WISPs operate more efficiently. After collecting data and conducting interviews, we came

[1] WISPA is the industry association for WISPs in the United States.

to realize that some of the assumptions we made were misguided. We initially expected WISPs in the US to face struggles similar to those described in the literature about wireless networks in the developing world [25]: flaky hardware, challenging fault diagnosis, and poor local IT expertise. This turned out not to be the case. In contrast to the "hacked together" wireless systems of the mid-2000s, technology, especially commodity wireless hardware, used by WISPs for building their networks has matured sufficiently that operators focus more of their effort on business development than technical issues. One WISP we spoke with in Colorado provided service over a 45,000 sq. mi. area with only 10 employees.

A common concern among WISPs in our study was spectrum scarcity. Of 43 respondents to the free-response question in our web survey "What is the biggest challenge your organization faces?", 22 (51%) expressed concerns relating to spectrum. The next most common group of concerns was around business development (23%), followed by affordability of upstream bandwidth and backhaul (16%). This was an unexpected result: we had anticipated issues around configuration and manageability of WISP networks to be a major concern, but this was not the case.

Spectrum. We asked about spectrum usage in our interviews. All of the rural WISP operators we interviewed operated in unlicensed spectrum, but many used some licensed spectrum as well. In particular, 7 of the 10 rural WISPs used the 3650MHz "lightly licensed" band, which has been very popular for WISP operators due to the relative quiet of the band compared to unlicensed ones. Multiple interview subjects expressed a desire to have spectrum set aside for WISPs due to overcrowding in the unlicensed bands. According to one operator, "basically, we need to use lots of bands because things are so crowded. [The 3.65GHz band] will never have home routers in it. So we can use, especially for backhaul, a relatively obscure chunk of spectrum." Higher frequency licensed spectrum (specifically, the 11GHz band) was used in some capacity by three of the respondents, primarily for high-capacity backhaul links.

On the surface, it surprising that spectrum scarcity would be an issue in areas that are largely underserved, but several factors make this an issue for WISPs. The WISPs we spoke with all had a limited number of tower sites for access points to connect customers to their networks. To reduce capital cost of expansion, these WISPs would take advantage of geographic features, re-use existing towers, or re-purpose other tall structures (e.g., grain silos) to avoid building new towers from scratch. Adding more subscribers thus meant co-locating more access points on each tower, leading to interference at the tower site. The second driver was foliage—WISPs serving forested areas reported heavy usage of 900MHz spectrum due to improved foliage penetration. The 900MHz band is the lowest-frequency band commonly available to WISPs, and is only 28MHz wide (compared to over 150MHz for the more commonly-used 5GHz band) yet is shared with a variety of non-WISP users, such as cordless phone systems and smart meters.

Business development and Financing. An unexpected theme that emerged was the difficulty of obtaining financing to expand network growth and meeting demand for service. Particularly for rural WISPs, the cost of adding a customer to the network is high, with an installation requiring a site survey, a trained technician, customer premises equipment, and physical installation of the hardware. Specifically, in our 2014 survey, we found that WISP growth was often constrained by financing once the natural (often geographic, though sometimes market, cultural, or political) boundaries of the WISP's growth had been reached, as the cost to grow beyond the boundary was a step function. Indeed, we found that this natural boundary to WISP growth seemed to have the same origin for many WISPs even if it manifested differently. For some WISPs, it appeared as though the WISP operators no longer had an interest in growing their network and reaching new users, but when pressed, this was because the cost (in time, effort, and money) was too great to take a step beyond the current size. For other WISPs this boundary manifested as a more straightforward financial limit to expansion—while the area in which they operated may have been profitable enough to sustain their current size, it was not able to produce enough profit to finance expansion into new markets.

A humorous but sobering comment from one WISP was that they switched to using minivans instead of trucks for service calls due to better fuel economy, yet still spend $2 per user per month on fuel. In an industry with an estimated ARPU of $30 [3], this represents almost 7% of gross revenue. One of our interview subjects stated that their ability to buy used equipment from a bankrupt competitor at a fraction of retail price was instrumental in allowing them to grow their revenue to sustainability.

Another unexpected theme in this area was the relationships among neighboring WISPs. Several of the WISPs we spoke with had cooperative, often informal, relationships with neighboring WISPs. These relationships included infrastructure and backhaul sharing, referring customers near the edge of one's service area to competitors, agreements to not expand into each other's service areas, and in one case even a co-op of several WISPs that made bulk equipment purchases and shared a customer support call center. Another common practice was WISPs buying out neighboring WISPs; three WISPs we spoke with reported having done this.

2.4 Discussion

Most WISPs we spoke with did not need network management tools to grow larger; their challenges were based on financial or regulatory issues. We argue that this is because they have typically already matured to natural size limits (or have failed). At those limits, even if the network is profitable it is likely unable to expand, constrained by inefficient network management and business processes, and unable to finance improving network performance. The high rate of startup failure and the low performance offered by many WISPs suggests that tools for facilitating the creation of new high-performance WISPs would be valuable. One of our 2012 interview subjects who both runs a WISP and consults for new WISPs went so far as to say, "I tell a lot of people that [running a WISP] becomes a lifestyle until you have people, because you have to babysit the network 24/7." Their advice to new WISPs starting out was to focus on automating and integrating as much of their backend processes (billing, subscriber authentication, etc) as possible to improve the odds the WISP would be able to sustain itself and grow. This insight was reflected throughout our interviews, would be reflected in our own experiences starting a WISP, and succinctly motivates the design of Celerate.

3. ASSUMPTIONS

With these results in mind, we now turn to the design of Celerate. We frame the discussion with a collection of assumptions that we brought to the problem. These assumptions are instructive: our exploration of them over the past decade has led us to hone the list of challenges to be addressed.

Target Rural Access. In urban areas density and existing infrastructure—e.g., right of ways for electricity, telephony, or sewage—make building infrastructure for Internet service delivery easier. Even where existing infrastructure deployment is chaotic and underprovisioned, the options available to serve users—wired or wireless—are better than those for rural areas. We thus focused our work on the task of connecting rural users, and began our work with the question: *how can we help rural ISPs scale?*

Design Choice	Reasoning	Comments
Unmodified Commodity Hardware	Wireless hardware is now cheap and high speed, but (sometimes intentionally) difficult to modify, and firmware such as OpenWrt seldom keeps pace.	With unmodified commodity gear, we can order and ship hardware directly to field sites for immediate deployment, simplifying our pipeline.
Community Relays	Many subscribers are quite close to our relay sites, but lack line of sight. Often one hop to a neighboring house allows us to reach them.	The radio gear necessary at these relays is not generally cost prohibitive, but deciding whether to provide power backups at these sites is difficult as power gear can be very expensive.
Unlicensed and Lightly-Licensed Bands	Hardware for unlicensed and lightly-licensed bands is affordable, and requires minimal hassle. Most WISPs use unlicensed hardware except in rare circumstances.	Using licensed spectrum is in keeping with our goals of matching the demands of WISPs. We do leverage several bands outside of conventional unlicensed spectrum, including those for which we have obtained experimental licenses.
Paid Service	A free network cannot sustain itself after our funding ends, and would not be reflective of a real WISP.	We had some free hotspots at central locations. After our research completes, the network will be handed off to a local nonprofit organization for long-term operation.
No Towers	Building towers is costly and risky, leveraging topography and existing structures is more efficient.	We have recently opted to build a compact tower, but it is one among dozens of sites at which we have avoided to build our own towers.

Table 2: Design choices we made for the rollout of our WISP deployment.

Greenfield is Valuable. As part of answering our question we decided to, and now have built, an ISP from scratch in a rural area in North America, in an area that had no fast or reliable Internet service options; those who had any service at all subscribed to satellite Internet providers. We might not have needed to build yet another ISP to learn lessons from it, but as we began our analysis of how rural ISPs were operated, we concluded that without a real network built from scratch we would inevitably fail to address subtle or seemingly-uninteresting pain points that prevent rural ISPs from starting up, growing, and operating.

Rural ISPs are WISPs. We assumed that rural ISPs are primarily wireless ISPs (WISPs). Specifically we are interested in WISPs of the sort that are built using low-cost point-to-multipoint wireless links, though some also employ wireless meshes and other approaches. We have found that this is true—nearly all rural ISPs are WISPs, though a small fraction still provide dialup service.[2]

Rural Access is Poor. Despite statistics and anecdotal reports to the contrary, our initial exploration of rural connectivity showed that, at least in North America, there is confusion about the state of rural broadband access. In meetings with many existing governmental and nonprofit stakeholders, we found that while the stakeholders' views aligned with ours—that rural access is poor—their *data and maps* said that's not the case. What we found was that since much of their data is submitted by large carriers that have an interest in overstating their coverage, the (inaccurate) maps that are used as ground truth prevent new entrants into rural markets.

SDN Eases Network Management. Our experience with both research and large-scale operational SDN networks indicated to us that SDN can significantly ease the challenges of network management. The promise of SDN is that it makes implementing network-wide policies simpler and eases management complexity in a network with many devices. This has been borne out in the datacenter context, especially in multitenant environments. However, to our knowledge there is little work on SDN or SDN-like architectures for WISPs, and thus it was part of our aim to test this assumption; we discuss this further in later sections.

Rural WISPs Want to Scale. Since our aim is to increase broadband Internet availability in regions that have perennially been without it, a natural aim is to help rural WISPs themselves scale. However, before our greenfield deployment, we were unsure of the pain points of today's WISPs—what is stopping rural WISPs from scaling? As a part of our effort to understand that, we spoke with numerous WISPs and we brought this assumption with us to those conversations: we assumed that rural WISPs want to scale and to serve a wider area; we expand upon this in the next section.

What we found was striking: WISPs reach their natural boundaries to their growth and stop growing (and often stop attempting to grow) at very small network sizes. Many WISPs are one or two person operations started by individuals without deep networking knowledge; once they became stable and had a user base, the operators ceased expansion. These WISPs typically reached the users within a well-defined geographic area, had set up gear such that it only needed occasional maintenance, and continued providing that service with minimal work thereafter. To expand for these WISPs meant trying to reach far away users, perhaps secure more rights of way, purchase more bandwidth, etc. It was in seeing these successful WISPs that were not growing (which were typically in the topographically easy to serve rural regions), and the WISPs that had failed, that we reframed our aims, as we describe with our next assumption. In large part, the reasons that WISP operators seemed hesitant to scale were not technological: each WISP is naturally limited, by people, finances, and geography.

Scale WISP Numbers, Not Size. After our conversations with WISPs we still believed that new systems and approaches would be valuable for WISPs and expanding rural broadband Internet availability, as many of the existing WISPs relied upon archaic systems to manage their operations when they used such systems at all—it was far from uncommon for a WISP operator to have little or no written or stored documentation of the WISP's topology, devices, configurations, address allocation, or policy. However since these WISPs were often not interested or able to scale their own operations because of non-technological limitations, we concluded that a reframing of the aims was necessary: our new aim is to determine how to scale WISPs in number, not in size. Thus we believe that *the fundamental challenge is to determine how to enable more people to start and operate successful rural WISPs.*

4. DEPLOYMENT

Our deployment provides broadband Internet access to a farming community and indigenous tribe in rural Northern California. In Table 2 we describe design choices we made for the deployment of our WISP network. A private grant covered the cost of physical infrastructure, putting us at a significant advantage over most small WISPs. We are not the first to serve this region, which has a population of only a few thousand individuals scattered in small towns

[2]We found dialup speeds are *decreasing* due to aging copper infrastructure; some areas we surveyed in 2014 get just 9600 baud.

Figure 1: A hillside relay site with a small mast we built to host multiple long-distance backhaul radios. At this site we host over a dozen backhaul radios and sectors (not pictured).

over a mountainous coastal region that is 75km North to South and 10km East to West. Indeed, over the past decade, we are aware of at least three other WISPs that have attempted to provide service to the region, and each failed.[3] What makes the lack of service in this region more remarkable is that there is buried long-haul fiber running through the region owned by two Tier-1 carriers, one of whom we negotiated with to purchase bandwidth.

4.1 Hardware

We use commodity hardware from vendors such as Ubiquiti [29] and Mikrotik [13] as most WISPs do. Commodity wireless gear has advanced considerably in the last few years. Several of our core links use Ubiquiti AirFiber systems [2] which cost about $1000 each and can, under ideal circumstances, provide full-duplex 1Gbps links over 10km. Even newer hardware from Ubiquiti and Mikrotik uses 802.11ac with point-to-point and point-to-multipoint radios and can provide hundreds of Mbps per link at much lower cost [14, 22]. Most of the radios in our deployment operate in the 5GHz ISM band, although we do use some devices that are in the 2.4GHz, 3.6GHz, and 24GHz bands in order to cope with a sometimes crowded spectrum. When unthrottled, many subscribers can get 30-60 Mbps symmetric throughput to the Internet with less than 5ms latency within our network, though we throttle them based upon their subscription plan. We also use fanless multi-port embedded Linux boxes at major infrastructure points.

Figure 1 shows directional backhaul radios on a short mast we built. The equipment pictured connects main sites with relatively high-bandwidth links (several hundred Mbps in good conditions). These sites host sector antennas aimed at subscribers who in turn have CPEs (customer-premises equipment) aimed back; some subscribers host short-hop wireless relays to other subscribers.

4.2 Software

Initially we began with the expectation that an SDN-based software stack, coupled with appropriate hardware in the field, might provide significant gains in the management of our network [15, 16, 18, 20]. However, we found the greatest benefit from our software for subscriber and network management. In parallel we have been developing relatively advanced SDN-based tools, but have not seen the value in deploying these in production and so have relegated them to a development testbed. We describe our work on this in Section 5. Our system integrates with Icinga, Cacti, and other classic monitoring tools, but is not tied to them.

[3] Anecdotally we learned that they failed due to a combination of technical, geographic, political, financial, and family issues.

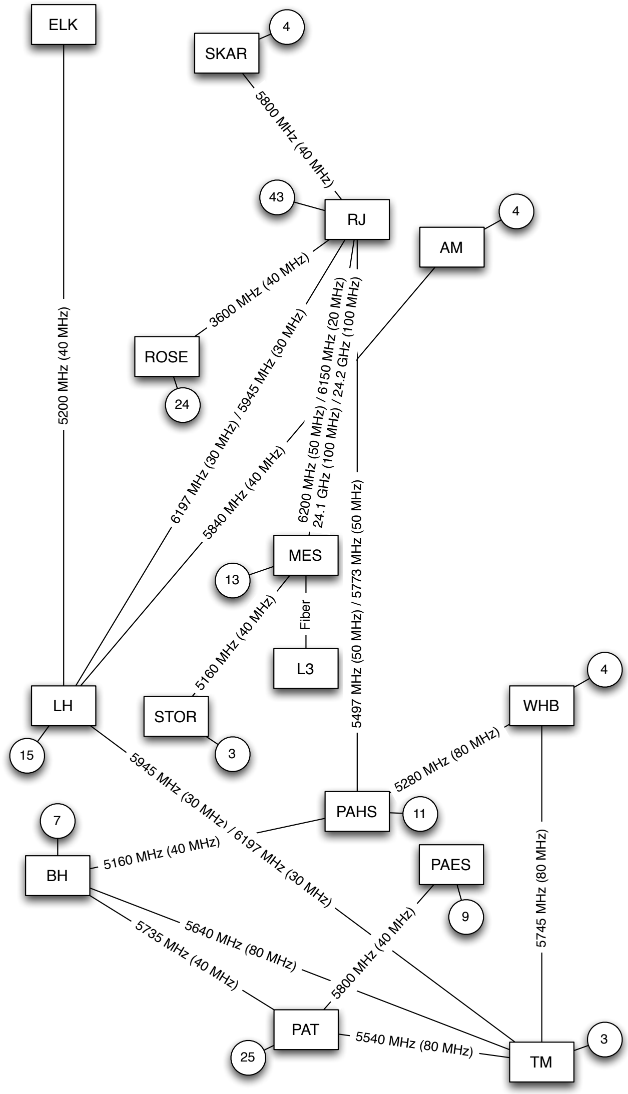

Figure 2: Our WISP network topology as of Q1 2015. Boxes are major sites, labeled by code names. Circles indicate the number of subscribers connected to those sites at that time. Lines depict backhaul links, with frequency and channel width; for full duplex links, we give TX/RX frequencies from South to North.

4.3 Network

Figure 2 shows our major sites and the point-to-point wireless backhaul links that interconnect them; while not to scale, the figure is topographically accurate. Due to numerous hills and forested areas, it is common, as the diagram shows, that nearby sites cannot communicate and must use far away relays. Not shown are the many sector antennas (base stations) that provide point-to-multipoint coverage for connections to subscribers. These sectors are the major source of spectrum contention and interference, which we discuss next. Core sites are bridged and use STP; subscriber nodes only have one path to the gateway.

4.4 Spectrum

Our deployment is in a very rural area, yet there is still significant spectrum contention. There is one other WISP in the region (there was yet another, but it shut down its operations recently), mostly serving different areas, and providing significantly lower

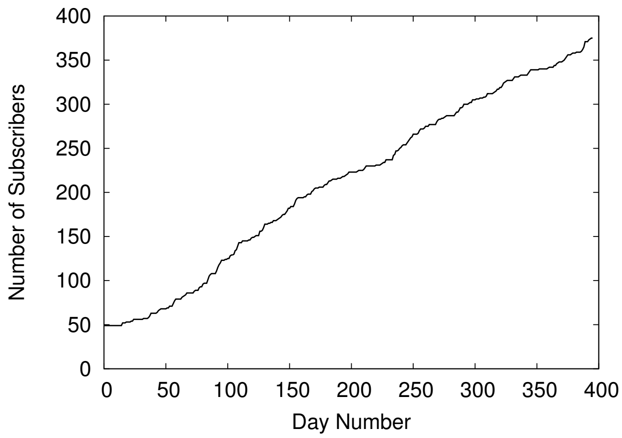

Figure 3: Paying subscribers in our network over time, from 2014-09-01 to 2015-10-01; we began with 49 beta subscribers.

bandwidths. However, we must share certain major sites, such as LH in Figure 2, quickly filling the limited unlicensed ISM bands. At one of our core sites, we have 5 backhaul links and 4 sector antennas that users connect to directly. As a result, we use a radio at 3.6GHz, 7 radios on 5GHz channels, and one radio on a 24GHz channel. The choice of frequencies for our radios at this and other core sites was done manually via careful planning and understanding of the topography, Fresnel zones, weather fade, potential reflections, trees, and spectrum congestion. We had hoped that automated tools, both third-party and our own fledgling efforts, might prove useful, but we found none able to handle the wide range of factors involved in making allocation decisions.

Spectrum regulations constrain our operation, but the situation is improving. For example, in April 2014, the U.S. FCC made several rule changes with regards to (U-NII) devices in the 5 GHz band. This included lifting restrictions on the lower U-NII-1 channels (5.15-5.25 GHz) which had previously been limited to low-power indoor use [10]. It also reiterated the necessity for radios operating on certain U-NII 5GHz channels to use Dynamic Frequency Selection (DFS), a standard for sharing spectrum between radar systems and WiFi devices (the primary and secondary users of this band, respectively). This standard requires secondary devices to listen before transmitting and to move to a different channel if the sense potentially interfering signals. A poor implementation of this can cause a radio to detect "interference" from its own reflected transmissions or choose poor channels to switch to when it must move; this was the cause of an intermittent outage we faced [1].

4.5 Growth

One of the key findings of Section 2 is that WISPs reach natural barriers during network growth: eventually WISPs tend to reach a maximum feasible size and stop growing without external financing. We already see hints of these limits in our own WISP deployment even though we are still in the early stages of network expansion. Figure 3 shows the number of paying subscribers connected to our network over time. The subscriber base of our network frequently reaches plateaus due to natural barriers—a hill beyond which our relays cannot see, for example. Due to our fortunate financial backing, we are often able to circumvent these natural barriers by building new, sometimes expensive relay sites, only to arrive at another barrier after a two-week spurt of growth. Recently we have found that the geographic reach of our network has made it difficult for our technicians to efficiently work at far-flung customer locations, relay sites, and storage sheds as many hours a day must be spent driving between them despite our best efforts at scheduling. Given our knowledge of the region, we expect our WISP to reach a final plateau at around 700 subscribers in about two years.

5. THE Celerate ARCHITECTURE

Next we describe the design and implementation of Celerate, an architecture for easing the startup and management of WISPs. We use Celerate to manage all aspects of our deployment. Celerate is a work in progress, and will likely require a few years of field deployment and additional refinement before it reaches maturity.

5.1 Challenges

Since Celerate is directly informed by the challenges we have encountered during our deployment and the findings of our WISP studies, we briefly describe the specific challenges that WISPs face that Celerate is designed to respond to. We emphasize that all the challenges listed in this section have both been borne out by our experience and were noted by our study participants. In this we keep squarely in focus our finding that the key way to increase rural broadband connectivity is to help create more WISPs rather than scale any individual WISP; these new WISP operators are unlikely to have the knowledge or training of existing WISP operators.

Skill Sets. Building a new WISP requires diverse skill sets. Many rural WISPs are operated by a single person, perhaps with part-time contract help for infrastructure work. At small scale, rural WISPs simply can't support a large team of specialists. Thus a single individual is tasked with challenges as diverse as tower and tree climbing, network architecture, carpentry, IP security, negotiating land use, spectrum management, customer support, billing, and reviewing legal agreements. Indeed, it is exactly because of this diversity of required skills—not commonly found in any one individual—that we hypothesized that new tools were needed for such rural WISP networks, to simplify the management of the network and give the WISP operator room to focus on physical infrastructure upgrades, maintenance, and customer support.

Commodity Gear. Almost all WISPs rely upon low-cost commodity wireless hardware and existing software; building custom hardware and implementing custom software is too time consuming, expensive, and requires skills beyond the average WISP operator. In turn commodity wireless hardware vendors operate with thin margins, and as such provide meager software support or flexibility for their hardware. As a result, network management systems, such as SDN systems, cannot leverage support in individual devices, but instead must manage a heterogeneous network of SDN-oblivious commodity devices each with their own quirks.

Operational Issues. The nature of and approaches to resolving operational issues differentiate WISPs from conventional operators. It is not that conventional ISPs or large network operators do not have many of the same operational challenges, but the issues they face are of a different scale: WISPs have a far lower ratio of human expertise and resources relative to the challenges faced in network operation and a far higher ratio of physical and operational challenges relative to the size of the network. This is largely due to dispersed, less-reliable infrastructure and more difficult deployment environments.

Geography and Land Use. In terms of performance, fixed wireless is almost always an inferior option to wired service, and thus is typically used when wired infrastructure is unavailable or is too expensive to deploy. Often, the causes for a lack of wired infrastructure is a lack of population density, rough terrain, or, more often, both. Thus WISPs begin with multiple disadvantages: they must

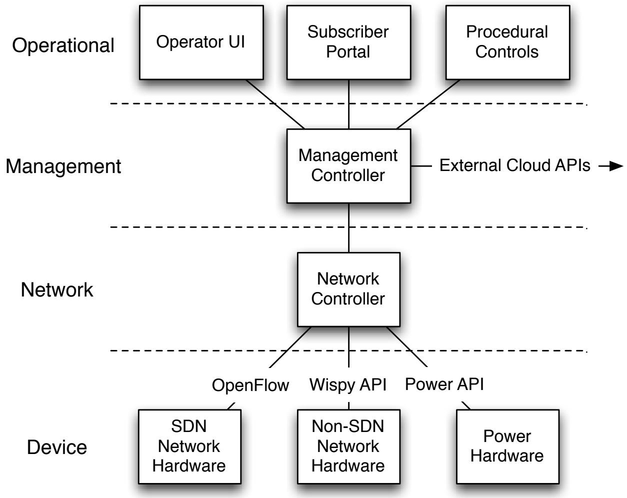

Figure 4: An overview of the subsystems in Celerate.

deliver service to a sparse region (thus making it hard to recoup fixed costs), using wireless instead of wired infrastructure, and do so over challenging terrain. Just because land is not developed in rural areas doesn't mean the landowner will make it available to a (cash-poor) WISP. Lack of existing tower infrastructure with good coverage of the region, especially line-of-sight coverage, means the WISP must build it or find an alternative. Indeed, the best prospects for placement of directional wireless gear is on existing structures such as water tanks, masts, sheds, barns, and the like.

Public Policy. Policy constraints tend to come in two forms: restrictions on spectrum, and restrictions on physical deployments. Spectrum restrictions are not new: WISPs are generally limited to operating on unlicensed spectrum only due to lack of licensing fees, but that spectrum is shared with a variety of other non-WISP devices, complicating spectrum planning. Physical restrictions typically take the form of regulations on tower construction and placement; for example, we found that placement of towers over a certain height under certain zoning required complex permitting and public approval, a process that can take a very long time and can easily end a WISP deployment before it begins.

Summary. The primary challenge posed by geography, land use, public policy, and similar non-technical issues is not the time it takes to resolve them—in due course, WISPs are able to resolve each issue in some way. Instead, the primary challenge is that these issues place non-technical constraints on the design of a WISP network and of the resources that can be deployed to parts of the network; they constrain how WISPs can manage networks on the ground and affect even what hardware they can deploy. It is within these constraints that we aim to address the above challenges to meet the needs of rural WISPs.

5.2 Subsystems

Many of the operational challenges in running a WISP are left out of traditional systems that aim to provide network management support. To make this clearer, next we differentiate between four subsystems of network management that make up Celerate: the device subsystem, the network subsystem, the management subsystem, and the operations subsystem, which we depict in Figure 4. Each of these subsystems corresponds to a plane that communicates with subsystems above and below. As we move up the hierarchy of subsystems from the device subsystem to the operations subsystem, we deal with a broader technical scope, greater complexity of mechanisms and policy, and slower timescales. Below we provide a sketch of our design for each subsystem and describe initial steps we have taken to realizing these subsystems. We do not claim that the overall structure or the individual pieces of Celerate are novel; indeed, much of it builds upon the canon of networking research over the past two decades. The key difference between Celerate and other network management systems is that it aims to be holistic, since we built it to address the real challenges we faced in building and running a WISP, and we use and improve our Celerate implementation on a daily basis. As mentioned earlier, we have found that the management and and operations subsystems to be most valuable in day-to-day operations.

5.2.1 Device Subsystem

The device subsystem corresponds to the traditional data plane in a networking context. In our context, however, the data plane is just a subset of functionality exposed. For example, in our deployment, the device subsystem includes SDN-enabled networking hardware, commodity non-SDN networking hardware, Power-over-Ethernet (PoE) switches with proprietary interfaces, power monitors, and battery systems. All of these devices provide interfaces for both control and monitoring, but they vary significantly in the interfaces they present. We are in the process of refining and developing APIs to manage these devices; the details of these APIs are relatively mundane, but are exactly what is needed to uniformly control devices that expose different types of functionality. At the moment we expose three APIs to the network controller above: OpenFlow; the Celerate API, which exposes common non-OpenFlow networking functionality such as advanced traffic shaping, SNMP, and wireless control; and the Power API, which exposes the ability to control and monitor power.

Many commodity networking devices actually run forked versions of OpenWrt [9] and thus could run standard Linux networking tools. However, the manufacturers add their own configuration mechanisms, generally in an effort to provide an easy to use GUI. Attempting to connect the network controller directly to these devices would leave a messy, tangled architecture.

5.2.2 Network Subsystem

The network subsytem includes the traditional SDN control plane, as well as extensions to integrate with our higher level management subsystem as well as the diversity of devices exposed by our underlying device subsystem (i.e., devices not traditionally managed by an SDN controller, such as battery backups). Our network subsystem consists of a traditional SDN controller (currently built upon POX [20]) suitably modified to address three of the key challenges we have in managing our dataplane. First, since the device subsystem is highly diverse, the SDN controller has to have support for APIs beyond OpenFlow. Second, the controller receives its ground truth not solely from the network, but as a synthesis of live status of the network from these diverse devices and management state from the subsystem above. Third, the controller requires the ability to speak with the device subsystem, but unlike many SDN deployments (such as in datacenters), we have no easy means of out-of-band communication between the controller and the devices it controls. Thus we have been developing an approach for broadcast-based in-band control for SDN, to ensure the network controller can always communicate with devices in the field.[4]

These two subsystems are the two that SDN typically is concerned with. Beyond them, in industry and academia, a large ar-

[4]We believe that this in-band control approach may have broader applicability, but is out of scope for this paper.

ray of diverse and incompatible approaches have been applied to higher subsystem management, usually tailored to specific applications and settings. To our knowledge, none of these higher-layer subsystem approaches are applicable to the unique needs of WISPs, and so we have designed our own, as we discuss next.

5.2.3 Management Subsystem

The management subsystem corresponds to the systems that track a range of information necessary for WISP management: network topology, physical deployments, network site documentation, and subscriber data including information about their physical installations, billing, and configurations. The management subsystem contains the ground truth about the network topology and about users of the network, and conveys this information downward to the network subsystem and upwards to the operations subsystem. We augment this ground truth with periodic automated discovery of new devices that are installed by technicians. We also integrate inventory tracking and management into Celerate.

Our management subsystem implementation is non-traditional for networking software, but an approach that is both flexible and easy to integrate with other systems: we use the Meteor Node.js (Javascript) framework, and our current implementation consists of over 5000 lines of Javascript, 2000 lines of front-end templating code, and hooks into numerous third-party modules and services that provide functionality, such as financial transaction processing, that must remain external to our system.

By separating the management and networking subsystems, we allow for the management subsystem to become disconnected or intermittently connected and not affect the operation of the network. In doing so, we can host and operate the management subsystem elsewhere (using cloud hosting), removing the burden from the WISP operator while not hurting the delivery of Internet service; setting up and running a cloud instance is, to our surprise, hard for some WISP operators we have spoken with, and so this separation allows us to offer it as a hosted service for other WISPs to use. In addition, the management controller can make calls to external cloud-based APIs, something that would be dangerous to do from the network controller.[5]

5.2.4 Operations Subsystem

Finally, the operations subsystem corresponds to the operators and the operational tools used to manage the entire WISP. The operations subsystem is largely human, but also consists of tools for managing and tracking operational and billing issues in the network, monitoring the status of the network, notifying operators about failures, and procedural controls to ensure that operator actions are constrained. This subsystem is a crucial aspect of SDN as applied to WISPs. Indeed, keeping track of subscriber relationship information is the core functionality a WISP needs, and thus is a core of Celerate. In addition, the operations subsystem enables an integrated view of all information needed by a WISP operator, from new-user signups to billing to link status and capacity to power status, and can present a network manager with an entirely new perspective on their network.[6] In addition, we provide a portal to subscribers similar to that of most large ISPs, so subscribers can see their plan information and pay their bill.

The Operator UI presents a user-friendly interface for technicians in the field to easily search and update this information. Indeed the user-friendliness of the interface, while far from the traditional challenges that are faced by SDN systems, is actually one of the most important, in our experience, to the overall usefulness of the system. Some of the most urgent software fixes we have made are when the operator interface has a bug that prevents field technicians from using it easily on their devices in the field.

While a WISP may have a very professional installation crew, depending upon them to configure hardware in the field—wireless spectrum, routing, services including logging and monitoring, etc.—can be putting too much weight on their shoulders. One of our long-term goals it to enable the operator—with the help of the network management system—to preconfigure devices which can be “plug-and-play”. Especially as a WISP starts and begins to grow, not requiring a networking expert to administrate the network can make the difference between success vs failure, or high vs low performance. We hope to deploy our prototype implementation of such support in our network in the coming months.

5.3 Status

We have been developing each of these subsystems independently, have built systems for each, and are integrating them, a process that we expect will require an additional feedback from deployment experience and iteration. Contrary to what we expected at the outset, we have found that we have reaped the most benefit from our work on the management and operations subsystems, and as such much of our development effort has gone into these tools. As a result, we currently use only the management and operations subsystems in our field deployment. Our field technicians have come to rely upon these tools and use them daily when planning, expanding, and debugging the network.

Our challenge has been to define what each subsystem provides to and needs from other subsystems. For example, now that we have delineated for what information the management subsystem holds the authoritative copy (e.g., network topology, power monitoring configurations) vs. the network subsystem (e.g., currently-active links based upon routing decisions, power-cutoff thresholds), there is the potential to fully integrate them.

6. RELATED WORK

For at least a decade researchers have advocated developing networking to meet the needs of poor and rural regions around the world [6]. The potential for WISPs to provide rural Internet access has been recognized for at least that long [4]. Prior work shows low-cost wireless hardware can deliver Internet access affordably and how to modify the MAC and PHY to improve performance [5, 8, 17, 23]. Similar techniques have been adopted by vendors of WISP hardware, making them available to the average WISP operator.

Surana et al. provided an early look at the operational challenges faced in rural wireless networks [25]. More recently, Rey-Moreno et al. describe lessons from the deployment of a community wireless mesh network [21]; this work however focuses on the particular challenges of operating a mesh network and in building a bottom-up community network. Similarly, Gabale et al. describe experiences from managing and a system for monitoring another rural mesh network [11]. While some of our findings and experiences overlap with those of prior work, we focus on the particular challenges around the *business* of operating rural WISPs.

Many WISP-specific management tools exist. HeyWhatsThat [12] is a mapping and link planning tool. Powercode [19],

[5]One of these external APIs is Stripe, a PCI-compliant credit card processing system which enables us to process credit-card payments without handling credit card data directly [24].

[6]This can be crucial in responding to weather. Our deployment region suffers from heavy storms, which can render our otherwise strong 24GHz backhaul link entirely unusable. We plan to leverage Celerate to enable an operator to anticipate this in advance based upon forecasts and adjust network flows accordingly.

Swiftfox [27], and Azotel [26] are commercial WISP management systems that provide subscriber, device, and network management tools; TowerDB is a similar open-source project. While exact feature sets vary, all of these and Celerate solve similar problems for WISP operators. Celerate differs from these by supporting deeper integration with network devices and is designed to be a modular, open-source, and SDN-capable platform for WISP management.

7. CONCLUSION AND FUTURE WORK

While our deployment and exploration of the benefits of improved management to WISPs is still young, we believe that our deployment has already showed, to us at least, that these approaches can help new WISPs start up and operate more smoothly. A local partner WISP has repeatedly asked for us to set up our systems for him as he sees that it will have immediate benefits for his operation, and we are in the process of doing so.

We expect that tying the wireless physical layer to SDN is likely to yield benefits for rural WISPs—especially when coordinated across multiple WISP operators—and will further simplify and automate these networks. Our long-term vision is of a WISP network that manages itself—a network that actively diagnoses failures and informs the local operator what to fix. While this vision is not a new one in networking, the context makes it particularly applicable, since WISPs are usually run by very small teams with limited skill diversity. Using SDN to globally coordinate the physical layer and network layer—taking into account RF connectivity, control of electronically steerable antennas, link bitrates, real-time workloads, and multiple backhaul paths through the network—would be beneficial for WISP networks (and would also be an attractive avenue of study, one which we plan to pursue).

We do not claim that our findings are the last word on WISPs, or are even necessarily broadly generalizable. Our surveys covered only a limited number of WISPs in North America, and our system design and experiences are inherently grounded in the particulars of our own network's history and evolution: if nothing else, our work shows that WISPs operate under a diversity of constraints, complexities, and circumstances. That said, our work does provide insight into the state of rural network development today, and importantly we have shown that the low-hanging fruit for WISP deployments comes from easing rather straightforward management burdens. WISPs are small operations constrained by their physical and economic environment, with stages of growth marked by jumps in capital expenditure. While the industry as a whole would benefit from regulatory changes like more allocation of spectrum for unlicensed use (which, happily, is a priority for the FCC), every small WISP that starts must to some extent re-invent and re-discover the best practices and systems necessary to run a sustainable network. To this end, we have developed Celerate as a modular and extensible system for WISP management that addresses the full stack of business concerns of the WISP. In doing so, we believe Celerate can serve to lower the difficulty of starting a WISP, increasing their number and improving access to Internet in rural areas.

8. ACKNOWLEDGEMENTS

We thank Eric Brewer, Jane Cavlina, Fred Coffman, Jason Coleman, Michael Hanson, Julie Lee, Jasper McMurtry, Zean Moore, Troy Nichols, Alex Papazoglou, Jenny Ryan, Krispin Scanlon-Hill, Scott Shenker, and Ron Steinherz for their assistance with this work, along with the Mendocino county community for their support of our efforts. This work was supported by a grant from Google.org and an NSF Graduate Research Fellowship.

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