Enabling Rural Connectivity with SDN

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ABSTRACT

The Software-Defined Networking (SDN) paradigm is typically applied to data center and enterprise networks. We argue that SDN is also promising for rural wireless networks, especially those in developing regions. Operating a rural network in the developing world means coping with unpredictability, low profit margins, and resource constraints; the increased flexibility and simplified management that software-defined networks provide are a major benefit in this context. Network virtualization, also enabled by SDN, would allow rural networks to operate as infrastructure providers to existing ISPs, thus enabling cooperation rather than competition with powerful incumbent providers.

1. INTRODUCTION

Almost four billion people – two thirds of the world's population – lack access to the Internet. Of those, over 90% are in the developing world, many of whom either live in rural locations far from existing Internet infrastructure, are too poor to afford connectivity, or face a combination of both [1, 8]. This situation is unfortunate, as Internet access can enable economic growth and enhance individual freedoms [17]. Businesses without reliable broadband Internet service cannot take advantage of cloud services and the efficiency benefits such services provide, nor can they engage with customers and suppliers electronically – practically a requirement for any business hoping to operate beyond their locality. Broadband Internet is being used to deliver cost-effective social services such as telemedicine [16] and distance education [15]. Even cell phone networks, arguably the most successful technology in terms of global adoption, rely on high-capacity backhaul to base stations to provide service. These use-cases and others demonstrate that increasing global broadband availability in these areas is a key international development challenge.[1]

Although Internet penetration is increasing, a disparity in access exists between comparatively wealthy, urban areas and poor, rural ones that is unlikely to change for the foreseeable future without a change in the underlying network technology. The latter are fundamentally difficult for Internet service providers to profitably serve: sparse population densities reduce opportunities for oversubscription, low purchasing power of potential customers implies small profit margins, and resource constraints make providing acceptable service quality hard. The history of rural wireless networks is rife with "pilot projects" that never reached meaningful scale or slowly fell apart when the (often US-university-affiliated) team who installed them left the area. Realizing the benefits of Internet access requires profitable Internet service providers whose customers trust them to provide reliable service over the long term. This requires innovation to drive down the costs of network operation and enable service providers to operate sustainable businesses, even in the most rural and poor areas.

Recent technical innovations such as modifying commodity 802.11 WiFi equipment for use at long distances (100+ km), coupled with novel deployment methodologies [9] have reduced costs at the physical layer, as have regulatory decisions to allocate microwave spectrum for unlicensed use. A new class of Internet service providers has developed as a result, which utilize point-to-point, "fixed wireless" access technology to provide service to remote, sparsely populated areas. We refer to such an organization as a *rural wireless network operator* (RWNO).[2]

Yet infrastructure cost is only one component of the cost structure for rural ISPs; profitable operation depends on controlling management and support costs. In this regard, a fundamental problem remains: rural wireless networks are highly variable, heterogeneous environments that are very difficult to manage, yet RWNOs must do so while understaffed and under severe resource constraints. Rural wireless network operators thus need a fundamentally new paradigm for network management; without solving this problem, RWNOs will not become widespread.

[1] We do not claim Internet access is a panacea for ending global poverty; clearly meeting basic human needs such as food, clean water, and healthcare are more immediate challenges. However, once basic needs are met, as is increasingly the case in all but the least developed countries, Internet connectivity can enhance existing capacity and drive further development.

[2] Such providers are also known as "wireless ISPs" (WISPs) or "fixed wireless broadband providers", though in this work we focus specifically on these networks in rural areas.

We believe that this challenge presents an important opportunity for the software-defined network community. SDN offers a principled approach to managing rural wireless networks and provides opportunities for making their operation simpler and more efficient, and may enable them to alter their fundamental business models. Specifically, by decoupling the control and data plane, SDN enables a RWNO to decouple *construction* of physical infrastructure, which must be done locally, from *configuration* of their network, which can be done remotely. Going further, this decoupling enables the infrastructure deployment business and the ISP business to be operated by *completely separate entities*. As a result, software-defined rural wireless networks can decrease costs and lower technical and business barriers to entry, thereby enabling profitable operation of rural RWNOs and expanding access to the Internet. For the SDN community, the rural wireless environment represents a radical departure from typical data center deployment environments. Rural networks are highly resource constrained, rely on aggressive traffic engineering, and present a dynamic physical environment that is difficult to manage. Thus, applying software-defined networks to rural wireless networks will "push the limits" of what is possible in SDN.

We acknowledge that SDN is not the only model that could enable the decoupling we discuss in this paper. That said, a key challenge for doing so in existing networks is the lack of a consistent global view of network state, as well as the lack of a standard interface a third party could use to configure an operator's network. Modern software-defined networks provide both of these. Existing SDN controllers and control protocols may even be adequate for RWNOs, though the rural wireless network environment is more heterogeneous and resource-constrained than the data center environment for which existing systems were designed.

In this paper, we explore the opportunity for software-defined networking in rural wireless networks. Section 2 describes the environment of a rural wireless network through a brief case study of a large rural wireless network in the Indian Himalayas. In Section 3, we discuss the role that SDN could play in such networks. We consider the implications of fully virtualized rural wireless networks in Section 4. We then present related work in Section 5 before concluding.

2. RURAL WIRELESS NETWORK OPERATORS

Rural wireless network operators have several defining characteristics and challenges that set them apart from other networks. In this section, we describe AirJaldi, a large rural wireless network operating in the Indian Himalayas. We also describe several actual operational experiences from the AirJaldi network. These illustrate the important yet unexpected issues faced by RWNOs in the developing world.

2.1 Case study: AirJaldi

AirJaldi is a social enterprise whose goal is to empower rural communities through provision of affordable, wireless, Internet access. Started in 2005 as a single-person operation in the Himalayan town of Dharamsala in India, the headquarters of the Tibetan government-in-exile, AirJaldi now operates multiple profitable networks spread across a number of Indian states. The largest network, in and around Dharamsala, serves approximately 10,000 users within a radius of 120km. AirJaldi uses outdoor 802.11 microwave radios in the 2.4 and 5.8GHz bands to link subscribers' rooftops to a central Internet gateway using relay stations on mountain tops. Some of the wireless links are 50km or longer, though the majority of subscribers are within 15km of a relay station. AirJaldi operates its own wireless backhaul links to connect to its upstream Internet providers in nearby cities or towns. The rapidly evolving upstream ISP market in India causes a relatively high churn in the number of upstream ISPs and total upstream capacity used by AirJaldi; at the time of this writing the upstream capacity of the Dharamsala network totals 15Mbps, primarily provided by two incumbent ISPs with additional ADSL lines from a 3rd ISP as backup and for congested hours.

The business unit in Dharamsala employs 20 permanent employees, half of whom are technical operators and installers. With the exception of a handful of top-tier subscribers, most clients enjoy a small subset of Internet protocols and applications; apart from web browsing, email and VoIP, most other ports are blocked for the majority of users. Moreover, most subscribers' web browsing is subjected to content filtering proxies to reduce bandwidth used for services such as pornography, rich media, and P2P file sharing. In addition, subscribers are subject to downstream bandwidth shaping based on the purchased plan (256kbps, 512kbps, *etc.*). These limits allow short-lived bursts to enjoy higher bandwidth and thereby satisfy most users better than competing non-burstable services such as ADSL. Network management is based on availability monitoring using pings from the central NOC using tools like Nagios [4] and a set of automated scripts to push configuration changes to remote routers. At the central Internet gateway, tools such as `ntop` [5] are used to observe network load and identify misbehaving flows. Manually configuring the network, with its high node churn, dynamic workloads, high failure rate, and frequent security incidents is a challenging undertaking, particularly when serving novice Internet users who are unfamiliar with the various failure modes of the network.

2.2 Tales from a RWNO

The experiences described below reflect actual operational events faced by AirJaldi network operators, providing a flavor of the type of technical and non-technical issues that further complicate network management for a RWNO. A large and well-trained staff would make most of these problems are trivial, but that is cost-prohibitive for a RWNO, and current techniques make automated solutions difficult.

Congestion and oversubscription. A subscriber calls the Network Operations Center (NOC) complaining about poor throughput on their connection. The operator notices a large amount of bandwidth being consumed by a major subscriber, company B. Because the NOC operator knows that company B is closed due to a holiday, this arouses suspicion; further investigation reveals a user at company B is accessing bandwidth-intensive pornographic content. The operator calls the CEO of the RWNO to approve routing company B's traffic through a content filter to reduce the volume of traffic. The CEO approves, and after implementing filtering, congestion at the RWNO's border link is greatly reduced.

Environmental issues, unreliable upstream, and tolerant users. It's monsoon season, and part of the RWNO's service area is hit by thunderstorms. Many subscribers in a particular district are disconnected, indicating failure of the local power grid (most of the RWNO's customer premises equipment is solar powered, so it can observe that customers' internal Ethernet links are down). Some hours later, one of the RWNO's two upstream providers goes down: it's a cellular operator with a central office in that district, and their batteries must have depleted after hours of power failure. Unfortunately, this failure occurs at a peak usage time, forcing the RWNO to scramble to cope with the loss of half its upstream bandwidth. All subscribers' traffic is routed through aggressive content filtering proxies, and all but a small number of well-known ports (e.g., 80, 443, 456) are blocked. The lowest tier of subscribers – free users who cannot afford to pay for services – are temporarily disconnected. As congestion worsens, more aggressive filters are put in place, blocking videos and security updates. Measures are necessarily heavy-handed, as the RWNO has no mechanisms in place to selectively throttle specific types of traffic or users. Despite this, no one calls to complain; in fact, users are surprised the service is up at all given the weather.

RF interference. A village the RWNO serves receives its water supply for two hours every Monday and Wednesday morning. The RWNO receives sporadic complaints of poor service quality in this village, and dispatches a technician to investigate. The technician determines the problems are due to RF interference, but the source of the interference is unknown, and even changing frequencies does not seem to help. After several weeks of investigation, they discover that an electrically ungrounded rooftop water pump was causing the interference; properly grounding the pump solves the problem. Despite its simple solution, a lack of monitoring tools prevented the RWNO from correlating failures and thus more quickly identifying the source of interference.

3. OPPORTUNITIES FOR SDN

Given the challenging management environment that rural wireless network operators face, we consider opportunities for software-defined networking to improve upon the status quo and facilitate the spread of Internet access.

3.1 Decoupling skills

Rural wireless network operators like AirJaldi perform two core operational tasks: construction of physical wireless infrastructure and configuration of that infrastructure. The skill sets required for each have little overlap, and thus a RWNO must either maintain separate staff for each or provide training in both areas to all their staff. Both options are expensive and inefficient. Technicians who install physical network and radio equipment must understand RF propagation and microwave link planning as well as construction techniques like tower climbing and safe wiring installation. These skills are completely different than those needed by technicians in the network operations center, whose job it is to ensure policy-compliant configuration and operation of the network. Yet for today's rural wireless operators, configuration and status monitoring is tightly coupled to the physical infrastructure they deploy. Adjusting configuration parameters on individual routers and access points is commonplace, and troubleshooting link failures requires understanding the full networking stack.

Software-defined networking enables network virtualization [10], which allows network operators to treat their physical network as an abstract pool of resource, specify management policy against this abstraction, and let the SDN controller handle the configuration of individual network components. In doing so they decouple the physical network from network policy. Decoupling these tasks also enables a rural network operator to decouple the staff responsible for each and increase specialization among their employees.

Specialization is generally more efficient for any organization, but it has particular benefits for rural network operators. Both physical and network configuration require specialized training, but all types of networks need network administrators, not just rural wireless networks. A capable network administrator can seek out jobs in both urban and rural areas, knowing their skills will be in demand anywhere. This is a serious problem for network operators in poor and rural regions: after investing the resources to train network administration staff, those staff could apply their skills in an urban area where increased business opportunities enable firms to offer higher wages. Rural-to-urban migration and "brain drain" is a problem in rural areas globally, and it particularly hurts rural parts of the developing world by sapping talent and expertise from areas that need both. In order to retain their network administrators, the rural RWNO would need to offer wages competitive with those of firms in urban areas, a financially untenable prospect.

In contrast, training physical installation technicians is a less risky investment for rural network operators. Physical installation skills are not easily transferable, nor is there a significant job market for such technicians in urban areas. The long-distance microwave links used by rural RWNOs are not practical in dense cities as the unobstructed line of sight such links require is not generally available. More fundamentally, the market for physical installation technicians is limited to organizations that operate radio equipment, as opposed to the wide range of organizations who need network administrators.

Decoupling these tasks enables a novel solution to this training and staffing challenge: outsourcing network management. Specifically, given a complete global view of network state and an abstract, logical model for the underlying physical network, control plane management can be conducted from anywhere, even urban areas. Architecturally, rural wireless network operators would run one or more SDN controllers within their own network, but the policy description for those controllers would be crafted by the operator's own network administrators or by a third-party network management consultancy to translate business needs and service agreements into a logical network configuration.

Outsourcing network management presents new – though arguably more tractable – issues for the RWNO. Network management outsourcing should not significantly impact performance or cause outages. For instance, the management outsourcing provider could also operate the RWNO's actual SDN controller, but this would require all policy decisions to incur WAN RTTs and expose control traffic to a higher likelihood of failure. Even if the RWNO operated their SDN controller in their own network, building a separate, reliable, "control channel" network is impractical; all control traffic must be transmitted in-band over links that may experience significant and non-uniform loss, congestion, and delay. As a result, deciding where in their network to place control logic is a non-trivial decision.

RESEARCH CHALLENGE 1. *Can software-defined networks be constructed to be resilient to unreliable control channels?*

RESEARCH CHALLENGE 2. *How does a RWNO verify their network has been configured as intended by the third-party management provider?*

3.2 Virtual circuits as policy abstraction

Internet service providers are in the business of providing service to their customers according to agreed upon service level expectations. Regardless of resource sharing, customers expect their service agreement to be met. This is indeed the key challenge for an ISP: oversubscribe one's infrastructure sufficiently to operate profitably while being able to deliver the expected level of service to clients.

ISPs today rely on the benefits of statistical multiplexing and heavy-handed throttling techniques to achieve this balance. Implementing effective traffic engineering requires configuration of individual elements of the operator's network. This situation is ludicrous; it is difficult to accurately specify a client's service requirements using these ad-hoc and limited-expressibility techniques, which are the only mechanisms current networks allow. Moreover, techniques such as bandwidth capping and shaping do not always reflect the reality of an ISP's cost model; as long as their network is uncongested an ISP has little incentive to limit usage.

RESEARCH CHALLENGE 3. *How can high-level policy declarations, including the sophisticated traffic engineering policies needed by RWNOs, be translated into concrete network configurations?*

Ideally, a RWNO would be able to allocate a per-customer virtual circuit from their network and then specify a set of service requirements for that *customer circuit*. Such requirements could include network properties such as bandwidth, latency, and jitter, as well as service level agreements specifying how frequently service requirements could go unmet. In addition to service requirements, a network operator could allocate middlebox processing services to such a circuit. This is essential in many bandwidth-constrained networks: in order to adequately serve any number of clients, extensive caching and content filtering must be employed.

3.3 Standardization of tools

A third key opportunity for software-defined networks in rural wireless networks arises from the fragmented ecosystem of currently available tools. RWNOs require a suite of tools for network monitoring, configuration, billing, and user authentication. Complicating the situation, tools from different vendors do not necessarily interoperate or expose common configuration interfaces. A similar situation exists for debugging and troubleshooting: with no unified or automated mechanisms for reasoning about the status of the whole network, operators are forced to rely on ad-hoc techniques for identifying and fixing faults. Individual RWNOs develop institutional knowledge to cope with this situation over time through experience, often learned the hard way.

This situation is akin to having unique programming languages and architectures for every organization that develops software. Developers could discuss best practices, but these would be of limited generality between shops. Sharing common libraries would be impossible – clearly a undesirable situation. Yet this is the status quo for RWNOs today; best practices are encoded in people, and the implementation of a best practice in a network is specific to its particular environment, precluding sharing. A solution naturally arises in an SDN: the controller presents a global view of network state, a well-defined API and programming model for accessing and modifying that state, and implicitly a standard abstraction for monitoring and managing equipment from multiple providers.

RESEARCH CHALLENGE 4. *How can management tools leverage an SDN controller's global network view to expose relevant network state to human operators, including those with limited expertise or who do not have easy physical access to network hardware?*

RESEARCH CHALLENGE 5. *How can operators develop "libraries" for fault identification and correction that are generic across networks?*

These are, in truth, engineering and product development challenges in addition to research ones. Yet solutions would be of immediate practical benefit to existing RWNOs. Thus, this is a point of leverage to drive adoption of software-defined networking in such networks.

4. TOWARDS A VIRTUAL RWNO

The opportunities for SDN described in Section 3 are each practical innovations that would directly impact rural wireless network operators as they build and manage their networks today. Yet the decoupling between construction and configuration that SDN provides also enables new business models for RWNOs. In particular, these two tasks can be conducted by *completely separate entities*. Such decoupling lends itself well to the franchise business model that has been successful for AirJaldi, in which regional operators focus on construction and maintenance of physical infrastructure while the parent company oversees the network management.

The logical extension of this idea is that RWNOs would, rather than acting as an ISP themselves, "rent out" their network to an established ISP. The task of the RWNO, then, becomes simply one of building wireless infrastructure and ensuring it can be managed by an SDN controller. This model radically changes the way RWNOs interact with existing telecoms. Rather than competing with incumbent telecoms, which often have monopoly status, government subsidy, or other strong competitive advantages, RWNOs are able to cooperate with an incumbent provider. In this arrangement, the RWNO provides an incumbent telecom access to new customers outside their existing service range. In return, the incumbent telecom brings their business expertise (and, if applicable, regulatory licenses) to the rural market. For example, billing customers with small and irregular incomes (as is common in the developing world [11]) is challenging. Large cellular service providers that serve remote areas face a similar problem, and have already developed payment infrastructures to cope with it [2, 13]. The RWNO can allow such a cellular service provider to offer Internet service over the RWNO's infrastructure and thus take advantage of the payment infrastructure the telecom may already have in place. The RWNO itself only needs to bill and interact with its ISP "customer".

The problem in this scenario is that end users in rural environments are subject to a non-competitive market for Internet service. Whatever ISP has an agreement with the local RWNO has, in effect, monopoly power, as building a competing wireless infrastructure is a significant barrier to entry for competitors. In the long term, we envision *virtual rural wireless network operators* which rent their infrastructure to multiple ISPs rather than only a single one. A fully virtualized RWNO would be an *infrastructure service provider*, analogous to the role that cloud providers such as Amazon's EC2 plays in the server hosting market. Rather than directly providing service to subscribers, the rural network operator would provide infrastructure to existing telecom and Internet service providers, its "client ISPs". The RWNO would present these service providers, its clients, with a virtualized abstraction of its network as presented by the SDN controller. Crucially, these ISP clients would be able to modify their slice's configuration without (non-programmatic) interaction with the VRWNO, just as users of cloud-hosted virtual machines require no interaction with their hosting provider to deploy new services. While the RWNO would still be responsible for building the physical infrastructure to connect their own network to potential clients, the subscriber would interact directly with the client ISP for billing and support. This model of service provision is also beneficial to consumers as it enables multiple Internet service providers to utilize the same physical infrastructure, thus increasing competition.

Once a client ISP obtains a virtual slice from the VRWNO they should be able to configure it using arbitrary control mechanisms. Moreover, client ISPs should be able to specify their own network configuration policies in arbitrary ways to suit their individual business needs. In order to reason about the degree of service they can offer to their clients, subscribers also desire consistent performance and network behavior – without these, the client ISPs cannot enter into meaningful service agreements with their customers. These needs lead to the following two key research challenges:

RESEARCH CHALLENGE 6. *How can multiple, independent network configuration policies co-exist on the same physical network infrastructure while ensuring safety properties?*

RESEARCH CHALLENGE 7. *To what degree can isolation between tenants' virtual network slices be guaranteed given a resource constrained underlying physical network with little redundancy?*

5. RELATED WORK

As far as we can tell, our work represents the first application of SDN technologies to resource-constrained wireless networks. The intellectual contribution of our work is an analysis of the technical challenges involved in adapting SDN to networks with bandwidth constraints, unreliable control- and data-channels, high churn rates, and a shortage of human technical expertise.

Network virtualization. Our concept of virtualized RWNOs, described in §4, is essentially an application of the network hypervisor pioneered by Casado et al. [10]; client ISPs define policies over their own logical network slice, which is mapped onto a single physical network. Similarly, the controller synchronization platform described in Onix [14] is directly relevant to achieving fault-tolerance and scalability in rural networks. The challenge in applying these technologies to the developing world is that unlike in the datacenter environment, rural wireless networks are loosely coupled, unreliable, and resource-constrained.

Cellular networks. The business aspect of virtual RWNOs is similar to roaming agreements in the cellular market: customers receive service from third-parties when outside their home service area, yet it appears to the customer that they are still receiving service from their own provider. Tower sharing schemes, in which multiple providers make use of shared tower sites and infrastructure, is used to reduce capital expense particularly in developing and rural markets. Incumbent providers may share infrastructure in ad-hoc arrangements, or through joint ventures into so-called “tower companies” [6]. While Mobile Virtual Network Operators (MVNOs), small providers who sell service directly to customers but do not own their own cellular infrastructure, are common, there is no equivalent concept of network virtualization in the cellular market, though multi-operator cellular base stations have been proposed [7].

SDN for wireless networks. The OpenRoads platform at Stanford University provides hardware, slicing between multiple tenants, and open APIs for experimenting with OpenFlow-based wireless networks [20]. Dely et al. further demonstrate the applicability of SDN concepts to wireless mesh networking [12] by using rapid OpenFlow updates to solve the host mobility problem. Our work expands this line of research into resource constrained wireless environments and considers the operational implications of SDN for rural operators.

Managing rural wireless networks. Most work on rural wireless networks has focused on the forwarding plane rather than the management plane. WiLDNet [16] and JaldiMAC [9] respectively propose MAC protocols for point-to-point and point-to-multipoint long-distance wireless networks for RWNOs, but do not consider how to manage large networks consisting of these links. Surana et al. [19, 18] describe a number of techniques for identifying faults in rural wireless networks as well as observed failure modes and practical solutions from field experience. Meraki offers a centralized, cloud-hosted network monitoring and management tool, though their offering is targeted towards well-provisioned enterprise environments as opposed to RWNOs [3].

6. CONCLUSION

Our vision for applying software defined networks to the rural wireless environment may seem unconventional on its surface, but in fact our proposal is quite modest in the context of the broader SDN community. Just like operators of large data center networks, RWNOs are not well served by the status quo for network management. Indeed, our agenda dovetails with current research trends in SDN. Consolidating control and management of a rural wireless network will simplify their operation, as will decoupling the tasks of infrastructure construction and network configuration. This decoupling further enables new cooperative business models for rural wireless networks. Taken together, we believe SDN has an important role to play in spreading sustainable, reliable Internet access to people worldwide.

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