Network Capacity as Common Pool Resource: Community-Based Congestion Management in a Community Network

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Congestion control mechanisms, by which network users share constrained capacity on Internet links, are heavily studied in computer science. Such mechanisms are traditionally automated, assuming that users do not wish to be involved in addressing congestion. However, in community-owned and operated networks, users have control over daily operational choices. We explore the design of community-based congestion policies and mechanisms, through the lens of network capacity as a Common Pool Resource (CPR).

Through a series of workshops and interviews in a rural community in Oaxaca, Mexico, we encounter design opportunities for new types of tools supporting communal network management. Participants expressed desires for preserving individual privacy while collecting longitudinal data to track the network's impact on the community, prioritization of high-value applications, equal link sharing between users, and human-mediated congestion management in lieu of automated enforcement. We report qualitative insights and offer design directions for future systems to address network resources in a manner compatible with Ostrom's principles for CPR governance.

CCS Concepts: • **Networks** → **Network management**; *Mobile networks*; • **Social and professional topics** → **Network access control**; • **Human-centered computing** → *Collaborative and social computing systems and tools*; Field studies.

Additional Key Words and Phrases: HCI for Development; Infrastructure; Rural Areas; Community Networks; Field Study

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1 INTRODUCTION

By ITU estimates, Internet connectivity has reached 51% of the world's population, bringing information access to a large percentage of people around the world. Yet despite this rapid diffusion, the expansion of Internet connectivity has slowed in recent years as relatively easier to serve markets saturate [58]. A disproportionately large percentage of the currently unconnected live in small remote communities which are difficult to access and serve with traditional centralized communications infrastructure [25, 27].

Community networking, the act of deploying, operating, and maintaining networks by and for community members themselves, offers a promising approach to bringing sustainable connectivity to these areas. Community network (CN) operators take advantage of local knowledge, social connections, and existing community resources to provide Internet connectivity with substantially lower capital and operational costs than traditional operators [1, 37].

As communities build and begin operating networks, physical limitations such as device power, legal limitations such as spectrum availability, and financial limitations, such as equipment cost, lead to practical constraints of the materialized network. Network congestion, the state of one or more of the network's links being insufficient to support the traffic generated by end-user applications, is a common phenomenon that results in poor quality of service and poor experiences using the network. In Internet Protocol (IP) networks, congestion causes packet delay and loss, experienced as slow page loads, stutters and drops in audio calls, or in extreme cases, resource timeouts that make entire sections of the modern web unavailable to these users [19].

We draw a distinction between congestion control, the automatic scaling-back of traffic to coordinate multiple devices on a network at machine-appropriate timescales (nanoseconds to seconds), and congestion management, the process of allocating bandwidth between users and tasks at human-appropriate timescales (minutes to years). Commercial Internet Service Providers (ISPs) traditionally perform congestion management through pricing, where users pay a higher price for a greater amount, faster rate, or increased Quality of Service (QoS) [13, 16, 26, 36, 53, 54, 59]. These policy decisions are then enforced through changes to network parameters which impact machine-level congestion control and ultimately users' traffic.

"Data plans" with a fixed speed (ie. 10Mbps) and/or quantity (i.e. 5GB) are straightforward and common, but lead to under-utilization and wasted capacity. Dynamic "smart data pricing" mechanisms are economically efficient [53], but are complex, can have adverse side-effects on real users who rarely act completely rationally [40], and break incentives when networks face divergent short and long-term objectives [48]. Managing congestion through pricing also introduces practical challenges to billing and payment collection [1]. Importantly, allocating resources via pricing in a community network can contradict the values inherent to that particular network [37], which may be modeled by its community as a public or common good inappropriate for pricing.

Drawing from our group's collective experience building and working in community networks, we hypothesized that existing economic theories of Common Pool Resource (CPR) Governance, formalized by Elinor Ostrom and the Bloomington School of Economics [11, 41], could apply to congestion management when pricing is inappropriate. While Ostrom's work focuses on physical resources such as fisheries or watersheds which are vulnerable to tragic long-term collapse [41, 42, 44], persistent network congestion collapse can lead to frustration and an inability to accomplish productive or time-sensitive tasks. Network congestion emerges when the collective demand of local users exceeds the carrying capacity of the network, mirroring how shared physical resources collapse in the existing economics literature. The research team has observed multi-hour outages where although a connection was available, even relatively lightweight mobile-optimized applications timed out and failed due to excessive congestion despite congestion control.

In this work we conduct an initial study of the feasibility and appropriateness of applying established CPR governance principles to community network congestion management. Management of a network with the principles outlined by Ostrom requires rules for access and allotment of resources in the face of scarcity that carry embedded values. As primarily ICTD researchers, we are sensitive to the centrality of the Global North to the design of existing tools for network management. We draw our methodology from elements of both Value Sensitive Design and Participatory Design, and solicit the users' feedback on a range of possible designs while probing the value tradeoffs embedded in each.

Working with a local partner, we held a series of workshops and interviews in Santa Inés, a small community with a history of communal resource management in Oaxaca, Mexico near Asunción Nochixtlán. We identify concerns held by members of the community around privacy and information in a locally owned IP network, explore values around how their community would define fair sharing of network throughput, and gather opinions for how such sharing should be structured. Community network management presents a unique challenge since operators often lack deep technical knowledge of how IP networks function [30], but are tasked with managing a network serving the entire town. At the same time, their responsibilities cross privacy and trust boundaries more typical of wide-area networks, serving a variety of users with whom they may have very different relationships.

We do not claim to establish which approach is best for this community or other communities in general, but identify directions for the design of future systems in this context which diverge from existing approaches. Among participants, we confirm a preference to avoid pricing-based mechanisms when allocating network resources and find desires to non-neutrally prioritize person-to-person communications, support local human-mediated management tools, and balance respect for individual data privacy with informed, community-based network governance. Our initial results support that Ostrom's CPR governance principles are compatible with the values of local users and could help structure efforts to achieve the goals identified by the workshop participants for the network.

2 RELATED WORK

2.1 Community Network Operations

A significant volume of work from CSCW, HCI, ICTD, and other non-academic contexts has explored the challenges of building and maintaining community networks. Examples of community networks include Guifi.net [2], Digital Tribal Village [51], TakNet [35], and many others. Community networks span a wide spectrum of organizational structures [37], with some growing organically as user-to-user meshes [12, 14], while others adopt more centralized but still community-oriented structures [2, 56].

Previous literature has explored long-term maintenance and upkeep of these networks, with Surana et al. describing early technical challenges in network maintenance [57], Bidwell examining the role of women in sustaining community networks in the Global South [4], Dye et al. documenting the care and inter-personal coordination of maintaining Havana's organic StreetNet [14], and Jang et al. exploring crowdsourced local repair [30]. In contrast to work focused on construction or repair, we consider the day-to-day resource management in an operational network, but which is constrained even in its fully operational state. Dye et al. do briefly discuss bandwidth management and conflict remediation practices implemented within the StreetNet organizational hierarchy, but in a very different context than Santa Inés. Our work additionally builds on theirs to explore a wider design space of possible management practices.

Prior work has also characterized how resource management impacts sustainable long-term operation of community networks. In African community networks, Rey-Moreno et al. [47] found that backhaul (the connection between the community network and the public Internet) bandwidth was a significant part of operational costs. This is the case in Santa Inés as well. Rey-Moreno et al. note the importance of local services to remove some pressure on the backhaul, but did not explore the details of how the limited bandwidth and network congestion was managed. Baig et al. [1] recounted the challenges scaling and managing resources within Guifi.net, the largest and most successful community network in the world. The Guifi.net model relies on a complex set of accounting and cost sharing agreements between operators and maintainers, and uses a traditional monthly billing model for end-users. In contrast, the network in Santa Inés operates at a much smaller scale and faces fundamentally different challenges since there is only one operator (the community's telecom coop) that operates much closer to its users. Additionally the dominating financial constraint in Santa Inés is the operational cost of a long-distance Internet connection rather than capital cost of new infrastructure.

2.2 Existing Approaches to Wide-Area Congestion Management

2.2.1 Pricing. Much scholarship has been dedicated to the question of how to price Internet and mobile phone services in the face of limited capacity and users' quality of service expectations. A first wave of Internet pricing research in the '90s and early 2000s focused around the challenges of using pricing to control demand and maintain service quality in rapidly growing Internet and mobile networks. A variety of pricing mechanisms based on auctions [36], congestion marking [18], priority bands [39], flows [31, 45], and hybrid approaches [60] were proposed, but Internet providers predominantly continued to use basic pricing schemes [40]. DaSilva [13] and Falkner et al. [16] survey this era of research.

A second era of pricing research began in the early 2010's and continues today. Sen et al. and Chiang et al. argue that "smart data pricing" is still relevant for congestion management in modern networks [10, 53, 54]. Ha et al., Joe-Wong et al., and Sen et al. argue for time dependent pricing in both fixed and mobile networks [21, 32, 55]. Ha et al. additionally developed a user-facing application, TUBE [23], to help end users manage the complexity of optimizing use under these time varying schemes.

While pricing has the advantage of good scaling properties, pricing may not always be appropriate in all contexts, particularly in close-knit communities like Santa Inés. In all of the research on economic means of network congestion management, relatively little exploration has been done towards non-pricing-based mechanisms. MacKie-Mason and Varian note as an aside: "There are many ways to deal with congestion externalities. One way is to establish social norms that penalize inappropriate behavior. Such norms can work well in small groups where there is repeated interaction, but they often do not scale well to a system with millions of users" [36]. In this work we explore whether non-pricing congestion control mechanisms and policies can apply to medium-sized groups of hundreds, not millions, and allow small community networks a different way to manage available capacity.

2.2.2 Embedded Automatic Protocols. "Congestion Control" is a well-studied technical domain in computer networking essential to the more general task of congestion management. In the Internet architecture, end-to-end transport protocols like TCP [6] or QUIC [34], using congestion control algorithms like CUBIC [22] or BBR [5], sense network congestion through packet loss or delay and then scale back the amount of data transmitted by each client until the congestion is resolved. These protocols are fundamental to the stability of Internet and largely operate automatically outside the knowledge of end users. Yet on extremely constrained links, like those found in remote networks like in Santa Inés, automatic congestion control protocols can only divide the limited resource so much. In a network serving tens to hundreds of users with only a few megabits per second of Internet throughput, this can result in per-flow allocations of 100Kbps or less, insufficient for the modern Internet. Higher level decisions about what traffic should be allowed when, and by whom, are required. We see low-level automatic techniques as compliments to, rather than replacements for, higher-level logic to manage network demand as explored in this work.

2.3 Existing Approaches to Home and Personal Connection Management

Insights from home and personal network management can also apply if we model a community network as an entity managed by a group of non-experts with a shared commercial backhaul connection and many connected devices. The CSCW and HCI communities have explored some of the approaches taken by individual users to manage their home connections. Grinter et al. [20] make a case for CSCW researchers to pay attention to how home networks are used, the maintenance and operations work that they generate, and their impact on the overall home environment. Yang et al. [61], Chetty et al. [7, 8], and Mortier et al. [38] develop and deploy several different home network management tools, delving into the social implications of revealing network status and giving network control to users in a shared space. These tools could be deployed as mobile applications or as views in a central management interface, but would not be appropriate for a context like the Santa Inés network (violating privacy values discussed in section 5.1.1). Chetty and Mortier both note social tensions and conflict caused by the information made visible and the control capabilities provided by their technologies. We anticipate that these issues would be exacerbated in the community network setting, where users have looser social connections and less frequent direct interaction, and designed our line of inquiry to explore these tensions.

Researchers have also examined how individual users manage their personal connections and developed a range of applications to assist in managing them under different network regimes. Chetty et al. developed uCap to help users plan for data caps in the home [9], Sambasivan et al. [49] developed SmartBrowse for managing mobile data consumption, and Ha et al.'s TUBE [23] allows users to automatically optimize consumption with time-varying prices. Im et al.'s AMUSE [29] helps users plan for when low-cost connections will likely be available, time shifting non-essential traffic. Similar tools could be deployed in the community networking context to help make users more aware of their consumption, smooth demand, and provide visibility to more effectively conserve network resources. While these applications give power and control to end-users, they all assume the network itself is fixed and that users interact with it independently. Community networks offer an additional opportunity, unconsidered in existing tools, for users to collectively optimize network policies that could lead to higher performance than individual-level optimizations alone.

2.4 Theoretical Framings

Throughout our work, we operationalize Ostrom's theory of Common Pool Resources (CPRs) [41] as well as Participatory and Value Sensitive Design (VSD) methodologies [17].

2.4.1 Common Pool Resource Governance. Within economics, significant study and theoretical work has been dedicated to the management and sustainability of common pool resources (CPRs), resources which can be appropriated (used) communally without private ownership, but can be overused without management and coordination. Elinor Ostrom's Nobel Prize-winning work [41] characterized successful and unsuccessful approaches to the management of common resources and popularized a framework for understanding how communities can effectively manage CPRs over time through collective action. Prior to her work, it was widely believed that the only ways to sustainably manage CPRs were external government regulation or privatization, but she finds

Table 1. A brief summary overview of Ostrom's design principles of CPR governance, detailed in Chapter 3 of Governing the Commons [41]. We find that congestion in the LTE network in Santa Inés could be managed in a way compatible with community values and all 8 principles, and discuss this further in sections 5.4 and 6.4.

CPR Design Principle	Summary Description
1. Clearly defined boundaries	The boundaries of the resource and those allowed to use it are defined and enforceable.
2. Congruence between appropriation and provision rules and local conditions	The way the resource is actually used is reflected in any rules applied, and those rules are responsive to changes in local conditions "on the ground".
3. Collective-choice arrangements	Most users impacted by operational rules can participate in rule modification.
4. Monitoring	Monitors are able to track use, and are accountable to local users or are local users themselves.
5. Graduated sanctions	Punishments for breaking rules are contextual and flexible given the seriousness of the offense.
6. Conflict-resolution mechanisms	Inevitably arising conflicts can be resolved quickly and at low cost.
7. Minimal recognition of rights to organize	The rights of users to organize and self-regulate are not challenged by external authorities.
8. Nested enterprises	If the CPR is part of a larger system, activities are organized in multiple layers.

stable counterexamples from a wide variety of real-world institutions, and devises game-theoretic models for how these counterexamples operate [43].

We conceptualize community network bandwidth as a Communal Pool Resource in Santa Inés, where network users are appropriators and network congestion corresponds to states of overuse. Prior works from Bernbom [3] and Hess [28] explore modeling the macro-scale Internet as a CPR using Ostrom's principles, but neither explore design implications nor consider how Ostrom's principles could be scaled appropriately to the community network context.

Ostrom outlines common principles shared by successful institutions (summarized in table 1), which we explore applying to community network congestion with the members of Santa Inés.

2.4.2 Participatory & Value Sensitive Design . Value Sensitive Design (VSD) methodologies as outlined by Friedman, et. al. are an attempt at supporting ethical technology design by investigating the relationship between human values and designs that may align or conflict with those values through their functions or affordances [17]. VSD proposes three major lines of investigation: conceptual, focusing on forming theories about stakeholders and their values; empirical, focusing on observing and clarifying stakeholders' competing values, practices, and motivations around use; and technical, focusing on properties and mechanisms of technology and the values that they support or hinder. We conduct participatory design workshops [33] with the help of our partner Rhizomatica to elicit Santa Inés network stakeholders' values and desires for network management, which will inform future technical designs for their network.

Fig. 1. From left to right: the trial LTE hardware, the view of the centro in Santa Inés, and the town hall and community telecom office.

3 CONTEXT

This research is part of a long-term collaboration between the researchers and Rhizomatica[1], a nonprofit organization specializing in rural connectivity and community media, to develop new forms of Internet-capable community networks. Here we outline the context to understand the community's current Internet access, unmet technical needs, and relationship with Rhizomatica.

3.1 Rhizomatica

Rhizomatica has operated in the Oaxaca region for the past 12 years, offering technical and legal support for the development of Community Cellular and Radio Networks. Rhizomatica's mission is "to increase access to and participation in telecommunications by supporting communities to build and maintain self-governed and owned communication infrastructure," through "regulatory activism and reform, critical engagement with technology and the development of decentralized telecommunications infrastructure, and direct community involvement and participation." They explicitly encourage local, value-sensitive governance of telecommunications, with implicit political biases towards local autonomy, sovereignty, and community solidarity. These biases come into play through Rhizomatica's role in workshop facilitation, subtly impacting themes and results. However, we perceive that Santa Inés's long-standing relationship with Rhizomatica has also led to general alignment on values and goals.

3.2 Santa Inés

Santa Inés can be broadly considered *rural*, which shapes residents' access to the Internet and other technical infrastructure. We follow Hardy, Wyche, and Veinot's recommendation [24] to characterize the research context's rurality along descriptive and sociocultural dimensions.

Santa Inés is a primarily agricultural area with around 1000 residents located 30km from Asunción Nochixtlán, the nearest larger town with a petrol station, supermarket, and high-speed connectivity. The surrounding terrain is rugged, with sharp hills and mountains on all sides. Regular communal taxis go between Santa Inés and Nochixtlán, 25 minutes each way (plus wait time to collect a full car). There is a strong sense of shared identity in Santa Inés, reinforced by multi-generational familial, economic, and geographic ties. A rotating local government is elected every 3 years to manage day-to-day operations, but all large decisions are put to a vote before "la asamblea," a

[1]Name anonymized for review

monthly meeting of all heads of household. Multiple participants mentioned a sense of duty to the community's welfare, for example to prioritize local over distant sales of corn in times of scarcity.

Wireless ISPs offer Internet connectivity for ~$50USD/Mbps/month, but few purchase a home connection since the links are expensive and unreliable. A shop and small cyber cafe in the town center sell hourly WiFi access ($0.50USD/hour), and there is a free connection and computer lab at the town hall. The free connection is time-limited per person per week since it is provided by the national government with an expensive satellite link. Santa Inés residents are not new to the Internet, but must travel to the town center or Nochixtlán for the services they need.

3.3 Existing Cellular Networks

3.3.1 2G Network Providing Congestion Management Experience. Santa Inés owns and operates a nonprofit GSM (2G) cellular network serving ~400 users, with technical assistance and training from Rhizomatica. The network provides calls and texts, both locally and with long-distance interconnect to the global phone network. Users pay a small monthly fee to become network "members," which grants unlimited local calling and texting, as well as the ability to receive calls from outside the community. Outbound long-distance calls are charged per minute depending on the destination, but rates are set as low as possible while covering costs. The network is a nonprofit, and the rates are generally considered reasonable by the residents.

The Santa Inés network only supports 15 simultaneous calls, and is commonly saturated since local calls are unlimited and free. Rather than putting a price on local calls, the community addresses congestion by limiting local calls to 5 minutes when the network is busy. This: a) breaks up long calls to allow new users to connect, and b) reminds local callers talking for a long time that they should consider continuing the conversation face-to-face.

3.3.2 LTE (4G) Network Trial and Adapting to Internet Congestion. Santa Inés community telecom and Rhizomatica are running a trial of a new LTE network to eventually provide high-speed Internet over a similar coverage area as their GSM network. It initially served ~15 users, and had expanded to ~40 by the end of this study. Rhizomatica has not decided how they would recommend Santa Inés manage network congestion in the LTE network and users had not yet considered the problem.

At the start of this research the trial network was operating as designed, but was already suffering from Internet congestion issues though the community had not identified them. The LTE and GSM networks shared their backhaul connection, and excess traffic from the LTE network was congesting this link, leading to packet loss which manifested as stuttering and dropout of long-distance GSM voice calls. Without management tools to make the problem visible or networking expertise to intuit what was happening, the president of the cooperative consulted the backhaul provider, who "fixed" the problem by disconnecting the LTE network.

3.4 A History of Communal Operations

Santa Inés has a history of communal resource management and established values around appropriate and inappropriate allocation of shared resources. For example, water resources are collected in a communally managed reservoir and a rotating committee is charged with allocating water fairly between different families based on the size of the household and each family's needs. Distribution is based around perceived fairness, rather than a cost per liter. Similarly, communal taxis charge a low flat price and pride themselves on delivering essential transportation to the community.

Funding to build the 2G cellular network's tower and purchase radio equipment was provided by the Santa Inés government, and the network occupies communal land and office space. Residents view the network as a shared resource which should be operated altruistically to the benefit of all. These values inform the network's management and pricing structures: the fixed monthly fee equally distributes the costs of maintenance and operations across all users, users pay at cost for long-distance calls, and local resource utilization is managed through the 5 minute local call limit applied equally to all when the network is busy. While there is a desire to apply the same high-level principles in the new LTE network, it is unclear how best to rectify the nature of modern Internet congestion with these existing values.

4 METHODOLOGY

Operationalizing elements of Participatory Design and Value Sensitive Design (see 2.4: Theoretical Framings), we sought viewpoints from multiple stakeholders, encouraged participants to think about community-wide interests and policy preferences, and explicitly elicited values associated with the network. Ostrom's principles informed our line of inquiry and helped structure our results. We adopted mainly empirical and technical VSD, using knowledge of cellular network affordances, combined with participatory methods, to reveal users' preferences and concerns and explore a wide space of possible congestion management strategies. In our analysis we synthesize our observations to develop a conceptual understanding of the values expressed and distill concepts to high-level themes such as *privacy* of usage data and *equality* regardless of financial means.

With Rhizomatica and the Santa Inés community telecom operator, we facilitated three public workshops to both educate the community about congestion in the LTE network and gather ideas for how to manage it. We also held two formal meetings with town leadership and conducted two opportunistic interviews. All interactions were in Spanish; the research team leads speak proficient Spanish and Rhizomatica staff are a mix of fluent and native speakers. Over the course of this research, one researcher lived in Santa Inés for a month and facilitated workshops 1 and 2. Two other researchers joined for two weeks at the end of the study for all meetings, interviews, and workshop 3. Even though it was not a research outcome, the researchers present in the community made themselves available to the network operator for direct assistance with the trial network, troubleshooting several technical issues and helping implement a rate limit in coordination with Rhizomatica at the operator's request.

4.1 Workshops

The workshops extended from the residents' existing understanding of management strategies used for different resources in Santa Inés, network management experience with their existing 2G cellular network, and exposure to commercial prepaid and postpaid plans used when outside Santa Inés. Two facilitators from Rhizomatica were present for all workshops in addition to the researchers. The workshops took place in an outdoor gathering space near the town hall, and were planned for an hour of content but tended to run long due to questions and discussion. The Santa Inés network's leadership suggested that the most people would be able to attend if the workshops were held in the early evenings on weekdays, and they scheduled each workshop. Participants were not monetarily compensated, but refreshments were provided to attendees. The workshops were approved by our University IRB.

Rhizomatica indicated that some participants would likely be illiterate, so the workshops were designed to not require individual literacy. All written artifacts pictured were discussed verbally and written by identified scribes. Consent to participate was gathered verbally as well, and written demographic surveys were not conducted. Audio recordings and the researchers' field notes are the primary outcomes of each workshop.

4.1.1 Workshop 1. Workshop 1 covered background of how the LTE network operates, how congestion impacts Internet networks, and generated initial use cases and ideas for congestion management. Participants were recruited from the general population of Santa Inés via a broadcast

Table 2. The count of participants in each workshop, their gender presentation, and the number of participants who were returning to participate in a second workshop.

	Total	Female	Male	Returning
Workshop 1	18	7	11	N/A
Workshop 2	6	4	2	2/6
Workshop 3	15	3	12	4/15

SMS message sent to all members of the 2G network two days beforehand. The operator also sent a broadcast reminder message and made a loudspeaker announcement in the town square half an hour before the workshop. 18 people participated (7 women & 11 men) and the workshop lasted for 1 hour and 40 minutes.

The workshop contained two parts, an overview of the network and congestion concepts introduced in a brief lecture, followed by an interactive question and answer session and large group discussion. Network congestion was explained (and discussed later) with both road traffic and carrying weight analogies to give an approachable way to relate to the abstract concept of congestion. Facilitators did not attempt to teach the details of how low-level protocols operate, but did offer feedback throughout the discussion that some strategies may be easier or harder to implement due to the types of information available in the network. Participants already understood that networks have a capacity limit from their experiences with the 2G network, and intuitively grasped the relative burdens different types of traffic place from experience with prepaid plans on commercial networks in larger cities.

The open discussion began by answering participants' questions about congestion and the differences between the new LTE network and the existing GSM network. After answering these questions, the facilitators steered the discussion towards the more open-ended topics of *Which applications and use cases are most important in Santa Inés?* and *What are some ideas for how the community could/should manage the network?* Facilitators emphasized that the network would belong to the people of Santa Inés at the end of the technical trial and that they had the agency to decide how they would like to operate it.

4.1.2 Workshop 2. Workshop 2 followed later in the same week as workshop 1, with the goal of generating more ideas for congestion management and making a rough rank order of the appeal of different policies. Participants were recruited through an announcement at the end of workshop 1 and a targeted SMS to residents using the trial LTE network or who had explicitly expressed interest in the LTE network to the telecom administrator. Workshop 2 had only 6 participants (4 women & 2 men), including 2 return participants from workshop 1, and lasted for 1 hour and 20 minutes. Workshop 2 was accidentally scheduled in conflict with a church service and following party which we believe limited participation in combination with the more focused recruiting.

Workshop 2 was structured as a group brainstorming session to explore possible network management approaches. The workshop began with a review of concepts from workshop 1 given by one of the returning participants with help from the facilitators. Afterwards the participants reviewed the ideas from workshop 1 and additional example proposals from the researchers, and then brainstormed new ideas together. For each idea, facilitators elicited the participants' thoughts about *Do you think this approach is a good or bad idea? Why?* and *How would this policy help or hinder using the network?* At the end of the workshop the participants came to a consensus on the top 3 ideas they would most like to see implemented.

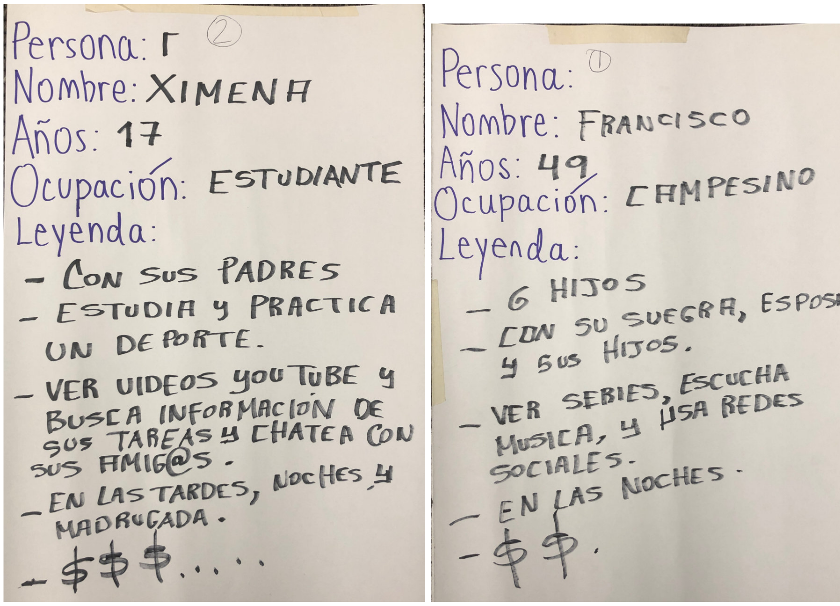

Fig. 2. Two of the five personas created for workshop 3. Personas contained basic demographic information, as well as a freeform "legend" section where participants could describe important parts of the persona's life, including how the persona interacts with the network.

4.1.3 Workshop 3. Workshop 3 followed two weeks later, and was designed to gather feedback and opinions on the proposals from a wide variety of participants. Participant recruiting was done via a broadcast SMS message one day in advance, with a personalized followup reminder message targeting users of the LTE trial network the afternoon before the workshop. Workshop 3 had 15 participants, 3 women and 12 men, and lasted 1 hour and 35 minutes. Three participants had been present during workshop 1, and one returned from workshop 2.

Workshop 3 began with the generation of 5 user personas [46], which were then used to evaluate sets of theoretical network policies. Participants divided into 5 groups, where each group represented a persona in addition to themselves. The researchers generated 5 sets of policies concretely implementing the ideas gathered in workshops 1 and 2, and presented these policies for evaluation. Unlike in workshops 1 and 2, the facilitators did not attempt to explicitly explain congestion, but provided a short practical example justifying each policy and then asked the participants *Is your profile in favor of this policy? Are you in favor of this policy? Why?* and *Does your profile thing this policy is fair and effective? Do you think this policy is fair and effective? Why or why not?* This sparked followup questions and debate, which the facilitation team encouraged.

4.2 Other Interactions

In addition to the main workshops, the field researchers arranged two meetings with Santa Inés' government authorities and the telecom coop leadership, and conducted two informal interviews. Only notes were taken during these conversations and after each interaction the research team met to debrief and record detailed notes. The researchers invited participants from workshops 1 and 2 to contact them through the telecom with any questions or if they wanted to share additional opinions, but none reached out.

4.2.1 Leadership Meetings. The first meeting took place between workshop 2 and workshop 3, and was attended by the mayor, two other government representatives, the cooperative president and treasurer, and the researchers. All non-researchers were male, and the meeting lasted for about half an hour. The researchers reviewed the policies gathered from the first two workshops to gauge their acceptability to these key stakeholders, and sought input from the leaders about what information they would want from the network to evaluate its utility to the community.

The second meeting took place in the afternoon before workshop 3 to include representatives from Rhizomatica who had come to facilitate the workshop. The mayor, two other government representatives, the cooperative president and treasurer, the cooperative network administrator, two residents, and two representatives from Rhizomatica were present. All non-researcher participants except the administrator were male, and the meeting lasted for approximately one hour. This meeting focused on setting boundaries for metadata collection, planning for future Internet health workshops hosted by Rhizomatica, and finalizing commitments between all parties for how results would be shared and next steps decided since the current study was coming to a close.

4.2.2 Impromptu Interviews. The field researchers interviewed one resident, a middle-aged woman and mother of three, who had befriended the researchers but was unable to attend the workshops. The interview focused on how she and her family would like to use the network, her opinions on the proposed policies from workshops 1 and 2, and her experience as a user of the current GSM network. The interview lasted approximately 40 minutes.

The field researchers also interviewed the telecom network administrator, a middle-aged woman. The interview focused on her experiences running the GSM network, and the processes and tools she uses for network management. The research team presented some of the metadata that could be gathered and used for administration of the LTE network, and sought her feedback on what information she felt would be most useful. The interview lasted approximately one hour.

4.3 Analysis

Transcripts were generated from the audio recordings of workshops 1 and 2, but the audio from workshop 3 was unfortunately unintelligible due to a microphone misconfiguration. The first and second author conducted thematic analysis on the transcripts and field notes, ultimately generating 103 codes grouped into relevant high-level themes. The researchers then examined the themes according to how they inform implementing Ostrom's CPR governance principles in this context. All participant responses in the paper are translated to English by the research team with names anonymized. Some responses from workshop 3 are paraphrased from field notes instead of quoted, indicated by *italic text* with no quotation marks. We shared a draft of this paper with Rhizomatica, who agreed it is a faithful representation of the field outcomes. We also shared a translated summary with the community via Rhizomatica, but have not received direct feedback.

4.4 Limitations

This study only includes one site, with a somewhat small sample size (33 unique participants) skewed towards men. Additionally, only a fraction of participants had direct experience with the LTE network at the time the study was conducted, and their views could change with experience and once possibilities are no longer hypothetical. The workshops were scheduled and advertised by the Santa Inés telecom authorities, and power dynamics and politics unobserved by the researchers and Rhizomatica could have impacted who chose to attend. There is also likely some bias introduced by Rhizomatica's participation in the workshop execution, since their existing relationship with Santa Inés would influence which topics participants chose to broach and elaborate.

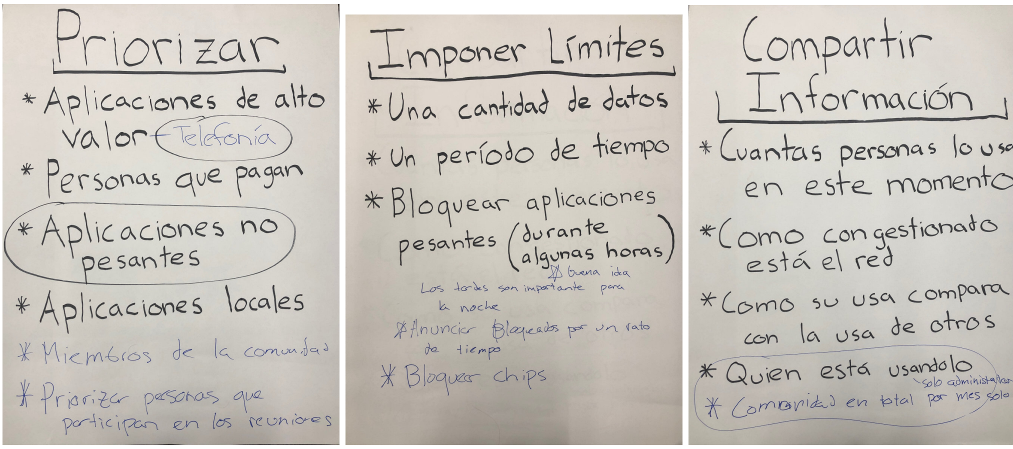

Fig. 3. Policy ideas generated and evaluated by participants in workshop 2. The top three policies are circled.

4.4.1 Transferablity & Reproducibility. The confluence of experience with communal infrastructure management (see 3.4) and ongoing engagement in community-based telecommunications (see 3.3.1) distinguishes Santa Inés as a research partner. Directly reproducing this study in another context will likely require additional capacity building prior to conducting workshops, but we believe that most insights from this work are not tightly coupled to Santa Inés and could be applied to designs for other community-area networks. Nevertheless, many of the insights in this study are particular to mid-sized "community-area" networks like the one in Santa Inés, which fall technologically and organizationally between wide-area networks (commonly operated by a third party provider) and local-area networks (commonly operated privately). Ostrom's principles may not be an appropriate model for understanding the dynamics of these distinct network structures, which have different sets of stakeholders and power dynamics.

5 FINDINGS

In this section we highlight common themes to inform the design of future community-based congestion management tools in Santa Inés and the values embedded within them.

5.1 Tradeoff between Individual Privacy and Collective Awareness

As in any network or platform, community networks' generated metadata is both a powerful tool for understanding the network and a liability to individual privacy. Participants understood this tradeoff and were willing to explore compromises between these two extremes.

5.1.1 Value of individual privacy. Many participants felt it was important that their individual usage not be exposed or recorded. There was some confusion about how much information could be seen by the network operator, but even when it was clear that the operator could not read individual messages due to encryption, these participants preferred that their individual app usage history not be recorded [2]. One participant offered (paraphrased) *I am a taxi driver, and some of my competitors live in this town. I don't just want everyone to be able to see how I am using my phone,*

[2]We believe it is worth noting that when asked directly, participants express a desire for individual privacy, but that most participants are using mainstream Internet applications which conduct substantial background tracking and hidden data collection [62].

what sites I visit, what messages I send. Maybe someone could use this information to steal my business secrets or my customers!

Participants were willing to allow an administrator to see the aggregated amount of data they use as long as it did not show specific sites and apps. This would allow identifying network hogs, but still provide some privacy. This arrangement is analogous to the policy used in Santa Inés's 2G billing system, where the administrator sees the total number of SMS and calls per user, but not the full call data record. In the LTE network people did not want any per-person statistics to be stored for longer than a month or two. The length of the telecom membership cycle is one month, so a short holding policy would allow investigation of any issues without preserving data unnecessarily.

5.1.2 Importance of collective awareness. The community in Santa Inés has an interest in understanding the long-term benefits or detriments of the network, since they are ultimately responsible for its operation. Yet the need for informative longitudinal data runs counter to the value placed on individual privacy discussed above. In traditional ISP networks, the disjoint nature of the user and the operator hides this tension, but it is readily apparent in the context of the Santa Inés network. We discuss this further in section 6.2. Participants were open to gathering aggregate statistics about usage of specific sites for the purposes of making decisions about the network, as long as they were for the whole community and not individuals. Participants suggested that this data could even be useful in developing workshops customized for Santa Inés to teach the tradeoffs of applications that see wide use.

5.2 Embodiment of Local Values

Since the network is owned and operated by the community, local values inform a locally appropriate definition of network fairness.

5.2.1 Allocate resources for each user. Participants discussed models for fairly allocating bandwidth in all three workshops. There was general agreement that all else being equal, instantaneous bandwidth should be divided per-user, not per-application as occurs naturally in IP networks. A user with a heavy application should not take up more of the link than other users with light-weight ones. In one representative exchange between a facilitator and a participant: "*How would you want to share the connection? If there are 200 people who want to use the half megabyte, should it be all equal? / Yes, everyone equal. / Per person, or per application? / It should be per person... yes, per person.*" While dividing bandwidth per user is an intuitive high-level concept, implementing it requires explicit traffic shaping in the network, and the community and Rhizomatica were previously unaware of these requirements.

5.2.2 Tradeoff between fairness and waste. Participants were more divided on the best way to define a fair distribution of data on longer timescales. Some advocated for daily or weekly data caps as is done in many commercial networks, since this is easily measurable, familiar, and treats everyone's data equally. Other users argued this would not be fair, since it would penalize those who want to use the network heavily when it is otherwise lightly loaded, leading to wasted resources. One participant in particular strongly advocated against data caps. Paraphrasing her argument: *it's not fair to have a daily quota if I am only in town on the weekend when there are not so many people. I hardly use the network at all during the week, and would lose that data. Even with a weekly quota, it's not fair. If the road is empty, why should someone have to pay extra to use it just because they already used their quota? It's a waste.* Others suggested that after exceeding the cap users should not be disconnected, but rather just deprioritized. Even this was controversial though, since responsible heavy use in the morning when the network is lightly loaded could make it harder to accomplish everyday tasks later in the day. In general, there was no clear consensus on whether it is fair to have someone's use (or lack of use) prior to the current moment impact the instantaneous allocation of bandwidth.

5.2.3 Opposition to paid priority. Some participants were in favor of allowing people to pay for extra capacity on the constrained backhaul link as long as this capacity did not come from the fixed capacity shared by the entire community. The distinction between whether a user is paying for extra backhaul or whether they are cutting in line on the shared communally purchased resource is subtle but extremely important. This point was debated extensively during workshop 3 due to a misunderstanding. Once participants realized that the facilitator was trying to propose that "paid priority" simply meant that the payer's traffic went first on the existing link, all participants immediately united to oppose the policy. One explained (paraphrased): *Just because someone has money, that doesn't mean that they can get special treatment or are more important than anyone else. This proposal goes against our values as a community.* An arrangement where additional funds went towards additional resources without taking away from the common allocation would be acceptable to some, but would require a new arrangement with the backhaul provider (who currently only offers a fixed rate service).

5.2.4 Concern for existing WiFi providers. Several participants expressed concerns about how a community data network would impact existing local businesses selling WiFi or computer access. The workshop attendees did not come to a conclusion about the best course of action, but did want to consider the impacts of any network on their fellow neighbors' businesses as the details of the network are finalized. One participant noted, *"It seems to me that the people who sell Internet, like Luis and Jose, are not going to stay in business. It won't work because people are going to prefer to pay monthly [with the community network], but currently have to pay per package (one hour session)."*

Some options discussed were explicitly restricting the community IP network to critical traffic to allow businesses to serve users seeking entertainment, or limiting the public network throughput to only a basic level. Limits on the public network would leave the businesses to offer higher speeds for a better browsing experience to those who need it. Another suggestion offered by Rhizomatica would be to involve these businesses in the operations and maintenance of the community network, since they already have some IP networking experience and could offer customer support. Participants did not come to a conclusion since details about the costs and capabilities of the community network after the trial have not been finalized.

5.2.5 Capacity building and preparedness. At several points during the workshops and in the meetings with leadership, the community expressed a desire for additional workshops and resources to better understand the network and how to be safe online. User education can be an important tool for long-term network health, and integration of information from the network with education could open up opportunities to better achieve the community's goals than could be done with network management alone. One resident elaborated, *"You know, the best thing you could do in the workshops, for example, would be to explain each app, if there are consequences to the application. For example, Youtube, gives this benefit, brings this cost, and Facebook, everything... we want to know really what each application brings to us."*

Participants suggested that locally accessible videos of any workshops or other educational materials would be useful. One community member proposed requiring all users complete some form of training before receiving full access to the network. This training could give users both an understanding of how their use impacts others in the community, and also resources to protect themselves and their families on the Internet.

5.3 Use Cases and Application Prioritization

The goals of the Santa Inés network's users shape the design of an appropriate network management approach. Participants identified calling or chatting with friends and family, listening to music, watching videos, using social networks, and searching for information as common tasks. Video streaming services like Youtube were mentioned as both a source of entertainment and educational content. Wikipedia was also commonly cited as an example of a useful information service, and one participant explicitly mentioned searching for concepts to help her son with his homework.

5.3.1 Importance vs. priority. Entertainment and media were clearly important use cases in the community; one participant noted (paraphrased): *a network that didn't support videos would be ineffective.* Even so, participants were enthusiastic about de-prioritizing bandwidth-hogging media applications if doing so would improve performance for high-value, if rarer, traffic such as emergency calls. While opposed to paid priority (see 5.2.3), participants were open to applying task-based prioritization equally across all users. Participants who discussed both prioritization and application blocking tended to prefer prioritization as a more flexible approach to traffic balancing. As a concrete example, in workshop 2 one participant proposed blocking video streaming during busy hours. Others responded that only de-prioritizing those applications would be better, since if the network were full they would be blocked, but if there was extra capacity it could be used and not go to waste.

5.3.2 Supporting person-to-person communication. Above all other use cases, participants consistently stressed that the network must provide reliable telecommunications for the community–that voice calls and messages are the most important function of the network. Calls and messaging allow community members to maintain social connections with far away family members as well as accomplish practical tasks like calling a taxi or ordering supplies from town. One participant put it plainly: *"What is the point of giving data to the whole community if we can't make a long distance call? Understand, most people just want to communicate with their family and friends."* When asked to select their top three desired features in the network, participants in workshop 2 agreed that prioritization of telephony was the single most important feature, and there was unanimous agreement in workshop 3 that telephony prioritization would be a good general policy.

5.3.3 Small applications. Most participants thought it would be a good idea to give preferential treatment to lightweight traffic that places a low burden on the network, especially after discussing the relative traffic magnitudes of different Internet activities. Participants grasped that prioritizing lightweight traffic makes it easier to interactively search and browse text information, while only slightly delaying heavy tasks like media streaming or file downloading. One facilitator was explaining, *"You can decide which applications are limited and which get more data..."* and a participant interrupted *"Ah, so for example Youtube could be last? ... This would be a good idea."*

5.3.4 Supporting education. Several participants raised the point that students often receive homework requiring the Internet for research or to watch an educational video, and that supporting education is one of the primary goals of the network. According to one, *"And here we need the [general] Internet connection above all, for the students."* A parent recounted that she and her school-aged son live in an outlying rancho, and they sometimes have trouble completing his homework if it requires the Internet. Either she has to wait in the town center after school while he completes the assignment, or if no computers are available, attempt to return later. Returning is a heavy cost in terms of both time and resources (in the form of gasoline with the family car or a taxi fare), and sometimes she tells him that he just won't be able to finish his homework that day.

5.3.5 Implementability. Not all proposed ideas are easily or sustainably implementable, and coming up with feasible approaches that can approximate or functionally replace other solutions is an important part of real-world system development. While control of the network is powerful, it is also limited by features of the modern Internet (https + encryption) that restrict the information available at the network layer. After learning about these restrictions, participants identified that it would be difficult to prioritize an important task (such as doing doing homework) when all the network can see is which addresses and sites are being accessed. One of the participants responded to a proposed deprioritization of Youtube: *"But then, let's say that we have done this and are watching Youtube, how slow is it? Can you? Now you can't. If one might want to look for information, then, you have to wait."*

5.4 Design for CPR Governance

In this section we synthesize our findings to identify design opportunities for supporting network congestion management compatible with the values and ideas expressed during the workshops while satisfying Ostrom's Principles for CPR Governance (see Table 3). Successful governance will enable the citizens of Santa Inés to control their own network, applying the resources of the network where they see them as most beneficial.

Santa Inés already has established practices and technology for maintaining boundaries (1), time-tested collective choice arrangements (3), and a recognized right to organize (7). The network is independent and small enough that nested enterprises (8) are not yet required. To support the remaining principles in a value-compatible manner, we see a need for new technical systems in the community network context enabling the creation and testing of network traffic policies, ethical data collection and monitoring, flexible sanction application, and efficient conflict resolution.

5.4.1 Congruence Between Appropriation and Provision Rules and Local Conditions (2). Ostrom's second principle addresses the ability to craft and adapt rules appropriate for changing local conditions. Participants proposed a wide range of theoretical policies, from priority access for attending training, to application bans, to quiet hours with limited speeds, among many others. However, with today's tools, it would be difficult for non-expert users to craft, experiment, and deploy arbitrary management policies. There is an opportunity to build functionality into the management system to support users in crafting new policies and testing their effects in a controlled setting. There is also an opportunity to support ongoing efforts in training, education, and capacity building by making network operation and status more transparent.

Data about collective use of the network will be needed to inform rule changes over time, but its collection should balance respect for individual privacy. Community leaders expressed a desire for operational data, but models for collecting useful longitudinal data for non-expert users, while maintaining individual privacy, agency, and data sovereignty, remain to be developed. Specifically, any deployed analysis tools must avoid storing detailed individual metadata traces, and will need to be flexible to support current use cases without precluding future policy evolution.

Supporting iterative, responsive decision-making aligns well with Ostrom's principles, but presents challenges when developing software. Current design best practices streamline information flow to preserve attention, but this assumes the designers can know what information is relevant, and often comes at the expense of adaptability to future unforeseen use cases. When discussing plans for the network, local leaders were hesitant to commit to a plan, preferring a flexible ad-hoc approach. The cooperative president remarked: *"We don't get even a megabyte with what we have right now, in the 4G [network], but it's the Internet... I don't know who it matters to, but if you all want to add a megabyte, it will be faster, I'll tell them [the provider] to add more Internet."* It will be

Table 3. This table details how Ostrom's principles can be operationalized for management of the Santa Inés community LTE network as a CPR. Asterisk entries (*) mark principles with a technological component, and **bold** entries indicate areas where the researchers hope to offer support through the participatory design process. We identify design opportunities to support rule creation (2) and enforcement mechanisms (5) in the network, as well as tradeoffs in providing a local admin with data and visibility into the network to facilitate monitoring (4) and conflict resolution (6) while respecting community privacy values.

CPR Design Principle	Santa Inés LTE Community Network as CPR
1. Clearly defined boundaries*	Potential users can be clearly delineated via possession of a network-specific SIM card required for access, and also blocked based on SIM card identity.
2. Congruence between appropriation and provision rules and local conditions*	Through participatory workshops and local governance structures, the community could craft rules such as cost structures and usage policies based on their needs and values. The rules could be updated as conditions change.
3. Collective-choice arrangements	Santa Inés has established governance structures for the telephony network, and users can modify management rules through collective action via the local government.
4. Monitoring*	A network admin, employed by and a member of Santa Inés, could observe others' usage through a management portal in a manner consistent with local privacy values.
5. Graduated sanctions*	Rules for sanctions, such as temporary blocking or de-prioritization, can be decided by the community along with other policies. A network admin can apply a range of sanctions on a case-by-case basis.
6. Conflict-resolution mechanisms*	The network admin can be consulted for minor conflict resolution, or serious issues can be escalated through existing community governance structures.
7. Minimal recognition of rights to organize	Independently managed community cellular networks in rural Mexico have been granted special permission to operate by the national government.
8. Nested enterprises	The community network operates independently and is small enough to be approachable.

important to build tools with flexibility in mind that communicate ground truth data in a way that could be applicable to a wide variety of policies and questions years down the road.

5.4.2 Monitoring (4). Monitoring resource appropriation is critical for preventing or penalizing excessive use. Participants desired a monitoring framework that could identify persistently heavy users while maintaining appropriate privacy safeguards, and supported establishing a position similar to the network admin in the 2G network. The admin would have privileged access to the monitor, and would rotate with the changing government duties in the town. Certain aspects of monitoring in the Santa Inés community network could be simpler than in a natural CPR (such as a fishery or forest), due to the ability to directly measure network traffic. Like the statistical data collection tool discussed in the previous section, a network monitoring tool will need to thoughtfully to preserve end-user values towards privacy and autonomy while still providing enough data to enforce flexible community rules.

5.4.3 Graduated Sanctions (5) & Dispute Resolution (6). Rather than attempting to encode strict rules in the network software, participants suggested deferring decisions when possible to a human administrator, as is done in the existing 2G network. The human in the loop can reach out via SMS to inform users if they are hogging or abusing the network, and apply rate limits or disable access only if they are non-responsive and continue bad behavior. An admin tasked with monitoring conditions during peak hours can identify problems, gather information both in-band and out-of-band, and implement reasonable, timely solutions taking into account all available context. Extending their toolkit for monitoring LTE network utilization and placing rate limits or bans on bad actors would be relatively straightforward, and allow more flexibility in enforcement than hard-coded rules.

There is also a design opportunity to facilitate communication and dispute resolution between the admin and users. On the management side, any tools should provide a means for the admin to save some kind of record of the behavior in question to consult when mediating a dispute. On the user side, network management tools should provide status to end users, allowing them to see if they are being sanctioned and why. A record should be kept of sanctions applied, so end users can appeal to higher authorities if they are being treated unfairly. While the admin is available in a physical office in the town center, sanctions should not prevent the user from using their phone to contact the admin or make an emergency call, since they may not be able to easily travel to the town center to otherwise discuss the problem.

6 DISCUSSION

6.1 Net Neutrality versus Network Ownership

Many of the congestion control/avoidance strategies discovered and discussed in the workshop run afoul of the principle of net neutrality: that network providers should not prioritize or block traffic based on the destination, application, or service [15]. For example, workshop contributors clearly indicated a preference for voice and messaging over other traffic. We believe these results speak strongly to the limitations of net neutrality policies in backhaul-limited and congested rural access networks. In these networks, there are both critically important services and limited capacity to handle all traffic. This combination requires network providers to have prioritization schemes (or congestion management) to resolve this conflict.

We aim to move away from simplistic notions of net neutrality, primarily a policy designed to keep powerful ISPs from engaging in business practices that harm customers, to network ownership, which is when users can decide network policies based on their needs. In this case, assuming ongoing community participation and ownership, traffic prioritization can be done in service of improved network performance and user experience. With network ownership, we believe that non-net neutral policies can be explored in more depth, especially mechanisms to ensure they remain in control of, and support, their users.

6.2 Privacy in Community Networks

Privacy is an important counterpoint to the above discussions on mediated access and community control. A strange advantage of the traditional ISP model is that service is provided by a large corporation which has (or should have) little interest in your daily life. With tight bonds between members of small communities, other users may have an unhealthy personal interest in your use (or non-use) of the network.

This will be a key challenge going forward, as the tension between providing a rich dataset for the community to use for decision making is inherently at odds with anonymous Internet access.

For example, a power user may be downloading too many movies via YouTube and need to be throttled. While inherently innocuous, this may cause the organizing committee to ask what videos are being seen and, even though the content in anonymized, they could continue to limit Internet access until that information is received.

This issue has come up before in our partner's GSM (2G) community networks. In a separate network, the community asked for the ability to gather call logs from the access point to monitor youth and shared accounts. This was not implemented by the partner, who was concerned it would create an incentive and means to monitor romantic relationships, specifically romantic partners.

6.3 Differing Scales of Congestion Control

Network congestion can happen at a number of time scales. It can happen at the millisecond scale when two competing services require more network capacity than is present. It can happen in the span of hours as multiple users, with services that require reasonable amounts of data, all sum to more than the network can handle. It can also happen over the course of a week, as the backhaul link temporarily fluctuates in capacity due to network failures outside of the community.

Each scale may require different congestion control mechanisms with differing levels of automation. The rapid microsecond congestion control remains the domain of traditional congestion control protocols such as TCP. At longer human-appropriate time scales, it may make more sense to allow operators to selectively disable or enable classes of service or switch entirely from one automated prioritization regime to another. We believe building usable network administration tools that embrace the time-varying nature of rural edge networks, at human time scales, could be an interesting new direction for research.

While participants proposed many automated mechanisms, such as the prioritization of certain content, there was also a repeated suggestion to designate a person "in charge" who could serve as a point of contact and leverage outside context and human sensibility in management decisions. Mediated access has a long history of research in ICTD [50], but in this case maps closely to governance structures already present in the community. In Santa Inés, individuals are given control over key community resources with the expectation that they are trained to maintain and support the infrastructure until their time has passed. Santa Inés uses a similar strategy to manage water resources, where trusted members of a water control committee have the authority to disperse allocations from a communal reservoir and responsibility to manage overall consumption to avoid a shortage. As such, developing congestion management mechanisms with a "human-in-the-loop," but that are compatible with individual Internet privacy and security expectations, is an exciting area of future research. We anticipate developing novel systems that both provide "knobs" for operator control as well as mechanisms for users to observe and interact with the operator's choices, such as network status and views into currently applied rules.

6.4 Technologies for Community-area Networks

Supporting infrastructure, both technical and non-technical, for community networks falls into an under-explored middle-ground between wide-area networks (e.g., regional ISPs), and local-area networks (e.g., home WiFi). In wide-area networks, powerful tools cater to professional network operators [52], providing advanced monitoring, filtering, and shaping capabilities. Yet they fall short in the community setting because they have a high usability threshold, gather and make visible too much data about individual users (see section 6.2), and assume a highly asymmetric power relationship between the operator and the end-user. They also lack affordances for transparent sanctions or dispute resolution like user-accessible sanction logs or a privacy-respecting means to store evidence of bad-behavior. In local-area networks, home-targeted tools have a lower usability threshold, but often lack facilities for flexible traffic shaping and don't integrate with commercial-grade cellular equipment (via DIAMETER and the Gx interface) to enforce radio resource limits or identity primitives like SIM-card authentication. Local-area tools also gather and make visible too much data about individuals, assuming all users are part of the same trust circle (whether it be a family or small business), and do not consider auditing and dispute resolution in their designs.

Building an effective community-area network management tool simultaneously compatible with Ostrom's Principles and the values expressed by workshop participants in Santa Inés will require re-evaluating design assumptions around the relationship between the network operator and end-users. Such a tool would require a mix of affordances from today's wide-area and local-area tools, while adding capabilities to support dispute resolution and balance end-user privacy with collective awareness of network operation.

6.4.1 Collateral Damage from the Surveillance/Privacy Arms Race. During the workshops, participants commonly desired high-level task-based policies, like prioritizing realtime voice calls, education, and messaging applications while deprioritizing entertainment videos. In practice though, Transport Layer Security (used by HTTPS) masks task information from the network, severely restricting what can be made visible for the sake of congestion management. The tension between privacy of content, and privacy of general task, is an important tradeoff in the community-area network setting rarely considered in wider Internet privacy discourse.

Quality of Service (commonly referred to as QoS) tags theoretically allow applications to signal how packets should be handled by the network, and can differentiate realtime communication traffic from background bulk transfers, but are often not implemented and subject to abuse. In a sample of three end-user devices in the Santa Inés LTE network, none consistently tagged packets from popular communication applications WhatsApp and Signal. Heuristics or AI-based classifiers on flow characteristics like protocol, address, packet size, and frequency can be developed for some tasks, but would be subject to errors which could exclude traffic the community would ideally want to prioritize and visa-versa.

Ultimately, reconsidering how much information is revealed to the network and fixing QoS tagging would require long-term changes across the device and application stack, but would open up new classes of enforceable management policies. Such changes do not preclude development of community management tools now, as long as such tools are flexible enough to make QoS, or some other type of task information, visible if it were to provide a meaningful signal.

7 FUTURE WORK

This study is part of a long term collaboration between the researchers, Rhizomatica, and Santa Inés. While we have identified several directions for future work, we plan to focus immediately on the co-design and development of appropriate tools to support an administrator in managing a small to medium sized community LTE network. In the long run, we hope to explore additional social mechanisms to improve the collective management of community IP networks, inspired by Ostrom's principles for common resource management and social-based conservation efforts. We also plan to perform a longitudinal field trial to gather both qualitative usability results and quantitative data on the effectiveness of these strategies at mitigating adverse congestion events in real-world community networks.

8 CONCLUSION

In this work we conducted initial design explorations of community-based systems for congestion management in a rural community LTE network. Through a series of participatory workshops, interviews, and discussions, we gathered a wide range of policy proposals and feedback on their feasibility and appropriateness to Santa Inés. Among participants, we found a desire to non-neutrally prioritize person-to-person communications, an aversion to pricing-based mechanisms for allocating network resources, support for human-in-the-loop local management tools, and an aspiration to balance respect for individual privacy with informed network governance. We see an opportunity to apply collective-action approaches, informed by Elinor Ostrom's Principles for CPR Governance, effectively in the community cellular network context for a more humanistic and flexible approach to community network governance than traditional pricing and automated congestion control.

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