Empowering Synergies of Communities with Service Providers for the Bottom-up Deployment of Network Infrastructures

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ABSTRACT

Ambitious plans for ubiquitous broadband connectivity call for huge investments in network infrastructures. Sharing the deployment costs of these infrastructures across multiple actors appears to be inevitable, but the exact form of sharing and the actual actors involved in it may vary. Our paper analyzes the role that community-driven initiatives such as Community Networks (CNs) could undertake in realizing these ambitious visions by making broadband network connectivity affordable in areas that do not attract original interest for private investments. Key to this role are open business models fostering synergies between typically non-profit CNs with commercial for-profit Internet Service Providers (SPs). In such synergies, the SPs make their pricing policies commensurate with the investment of the community, in order to fuel the CN growth and generate a market for their services. At the same time, they compete with each other for customer shares in this market. We capture the strategic interactions of the actors into a leader-follower game and compute numerically its equilibrium states under a broad range of scenarios constructed out of real data. In all cases, our results point to mutual profits for all actors, turning such synergies to win-win strategies.

CCS CONCEPTS

• **Networks** → *Network economics*; *Network performance analysis.*

KEYWORDS

Network infrastructures, community networks, pricing, game theory, cost-sharing mechanisms

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1 INTRODUCTION

Ambitious plans for fixed broadband connectivity such as the Broadband Europe 2025 agenda [1] or the more universal 5G [4] and 6G [23] visions for the next generation of mobile cellular systems call for huge investments in network infrastructures. These investments primarily relate to digging costs and rights of way for deploying fiber cables, either as ingredients of fixed access technologies (Fiber to the Curb/Home) or as backhaul support for the 5G and beyond radio access networks. Sharing the infrastructures and their deployment costs appears to be inevitable and motivates diverse models of cooperation and competition between different business actors in the telecom sector (network infrastructure providers, network operators, service providers) across the world [15].

At the same time, ITU [14] and OECD [21] have been promoting for over a decade now the network infrastructure separation and sharing through legislation, regulation and subsidies. Key to this end is the adoption of open-access network models that separate the ownership from the use of different infrastructure layers, enabling the sharing of the network infrastructure costs and fostering competition. Those models strongly differentiate from their vertically integrated counterparts, where the ownership and operation of network infrastructure and, even aspects of service provision, are concentrated in a single entity.

In this paper, we take a closer look at the implications of such layered models for the provision of Internet access services. The involvement of multiple actors and the different ways they can share the network infrastructure costs result in richer interactions between the actors than in vertically integrated models. It is, hence, more challenging to identify conditions that render infrastructure sharing profitable for all involved actors and ensure the business model sustainability.

We particularly address in our work the dynamics brought to infrastructure sharing by grassroots initiatives for network infrastructure deployment such as community networks (CNs). CNs are typically launched and managed by communities of people, who collectively contribute time, effort and resources to their purpose. Over the last fifteen years, CNs have repeatedly proven their potential to leverage the social links and resources of communities and deploy network infrastructure for high-speed Internet access in areas, where investments from commercial operators were deemed non-profitable. Nowadays, in view of ambitious yet costly connectivity agendas, CNs could evolve to a catalyst of synergies between different telecom business actors for the economically sustainable deployment of network infrastructures. Since 5G technology could take years to materialize beyond densely populated urban areas [17], such synergies may accelerate the deployment of network infrastructures and foster equitable access to the Internet.

We explore these synergies through the lens of network economics. As with prior work in the literature of shared network infrastructures, we consider a business model, where a distinct

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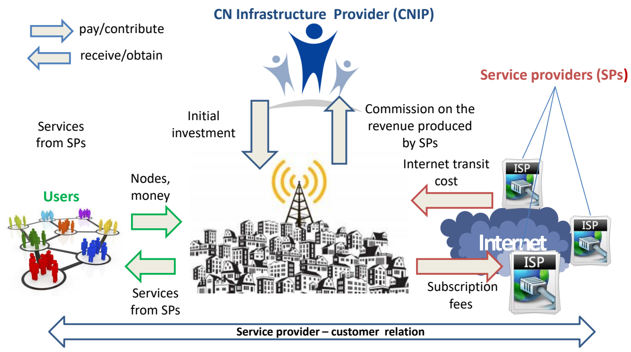


Figure 1: The actors in the shared infrastructures model.

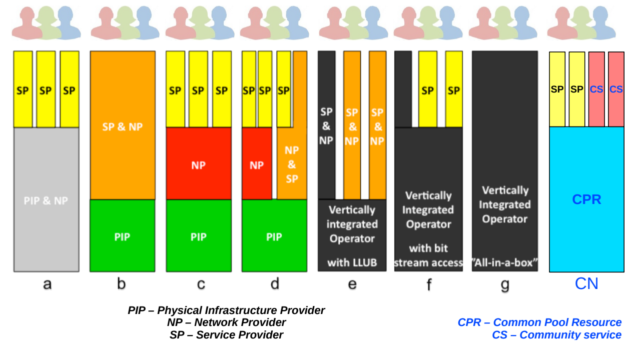


Figure 2: Layers of a broadband network (adapted from [12]).

actor undertakes the role of network infrastructure provider. However, contrary to almost all these studies, the network infrastructure is under the responsibility of a CN infrastructure provider (CNIP), which denotes the team of people who originally launch and operate the CN. They make an initial investment in the CN, setting up the first nodes that form an island of connectivity. Then, the end users join the CN with their own equipment and grow this infrastructure further, letting even more users join the CN. They do so to get access to Internet services provided by commercial Service Providers (SPs) who compete for customers through their pricing policies, as shown in Fig. 1. Part of the revenue they generate from customers is returned to the CNIP for the maintenance of the network infrastructure and Internet transit service costs.

Such a model bears potential benefits for all three types of involved actors. The CN infrastructure provider can expect more users to join the CN since they are far more interested in Internet access than local services that can be delivered without Internet connectivity [19]. At the same time, it secures the sustainability of the initiative and offloads the burden of collecting user monetary contributions for network maintenance costs to the SPs, thus avoiding free-riding effects that are usual within such communities [8]. SPs save the upfront costs of infrastructure deployment and gain access to "markets" that would be otherwise inapproachable. Finally, end users have a chance to get affordable access to Internet. Whether the potential benefits will turn to actual ones depends on the original investment of the CNIP, the pricing policies of the SPs and the response of users to them. These jointly determine the resulting coverage of the CN, the market share attracted by each SP and, eventually, the profit or loss of all involved actors.

Our contributions could be summarized as follows:

- We formulate the non-trivial interactions between the CNIP and the SPs as a leader-follower game in section 4. This process involves modeling the CN infrastructure growth, the service provision processes and the cost-sharing rule that determines how SPs share the CN infrastructure costs (section 3).
- We compute the equilibrium states of the game in section 5 and assess their fitness through a cost *vs.* revenue analysis for all actors.
- We discuss the implications of this assessment for the sustainability of the synergy and draw instructive hints for individual actors.

Before proceeding with the main paper contributions, we discuss the layered open access model and related work in infrastructure sharing in section 2.

2 BACKGROUND AND RELATED WORK

2.1 Background

In our work, we draw on open-access models for broadband network infrastructure and services such as the one in Fig. 2 [12]. In such models the overall network functionality can be structured into three distinct but inter-dependent layers: a) *passive infrastructure*, b) *active infrastructure* and c) *services*. Telecom operators and private companies, public authorities, but also local cooperatives and housing associations may assume roles at one or more of these three layers.

The *passive infrastructure layer* includes physical infrastructure that depends on the link technology in use, *e.g.*, fiber, copper, radio. Part of this infrastructure layer are ducts, cables, masts, towers and other equipment of non-electronic nature with lifetime in the order of decades. Its development typically demands high capital expenditure (CAPEX) and does not favor frequent upgrades. Its operational expenses (OPEX) are relatively low. The passive equipment is owned, maintained and operated by the *physical infrastructure provider (PIP)*.

The *active infrastructure* layer denotes electronic physical equipment such as routers, switches, antennas, transponders, control and management servers. The OPEX of the active equipment (*e.g.*, electricity costs) is high but its capital expenditure is comparatively low. The active equipment needs to follow the advances of technology and get renewed frequently, *i.e.*, more than once within a decade. The *network provider (NP)* operates the active equipment. It leases physical infrastructure installations from the PIPs and makes its equipment available for the provision of services by SPs. Network providers are most often private companies and less often public authorities or local cooperatives. They may own the equipment or subcontract it from entities owning it.

Finally, the *service* layer corresponds to the telecommunication services, such as Internet access, telephony (*e.g.*, VoIP) and access to media content (TV, radio, movies), provided on top of the passive and active infrastructure by *Service Providers*. They are typically for-profit companies that utilize the network's active and passive equipment to offer their services to end users in exchange for monetary compensation. They need access to the NP's interface and install their own devices if and where needed.

Figure 2 then captures the models that can emerge with respect to the functional separation across the three layers[14]. Although the borderline between the respective actors is not always clear-cut, they range all the way from variants of vertical integration in *e, f, g*, to partial role separation in *a, b, d*, and full functional separation in *c*. For example, the municipal fiber cable network of Stockholm called Stokab (*https://stokab.se/en/stokab*), is an example of case *d*. The municipality-owned company undertakes the role of PIP and multiple NPs may access its dark fiber infrastructure. On the other hand, Mobile Virtual Network Operators (MVNOs) almost always set examples of case *e*, leasing network resources from a Mobile Network Operator (MNO). Community network infrastructures, which are the focus of this work, represent a distinct case in Fig. 2 (denoted as CN), where the network infrastructure, both passive and active, are a community resource. Service providers then deliver services on top of it under a commons license [5]. This is the scenario we analyze further in sections 3-5.

2.2 Related work

In [11] the authors propose resource-sharing and payment mechanisms drawing on optimal auction and mechanism design techniques so as to maximize social efficiency. Participants are strategic in revealing private information about their resource needs. Resource-sharing mechanisms should incentivize participants so that they contribute to the infrastructure and cover their costs. A different setting in resource sharing is considered in [24], where players compete for location-specific resources. The authors consider the limit of a large number of players and employ mean-field theory to show that the equilibrium has a threshold structure, according to which a player switches to a different location based on the numbers of resources and players at the current location. In cellular mobile networks, infrastructure sharing among different Mobile Network Operators (MNOs) is rather common practice since the years of second and third generation networks and it is considered almost mandatory for 5G networks as well [7]. Optimal infrastructure sharing of co-existing MNOs is studied in [9]. Each MNO decides whether to deploy more base stations and share them with other MNOs so as to maximize provisioned rate to its users. The global optimal strategy of maximizing total rate is derived through a mixed-integer linear program, while the individual perspective of each MNO is studied through nontransferrable-utility coalitional games.

On the CN front, the Guifi.net CN in Catalonia, Spain, has explored possible synergies with for-profit business actors [5], engineering cost-sharing rules that split Internet transit costs among commercial entities that use its network infrastructure for providing services. In [10], these rules are analyzed and shown to be achieving cost shares resembling those of the Shapley value. Our work is, to the best of our knowledge, the first attempt to provide evidence for the feasibility of synergies between communities and commercial entities around the deployment of network infrastructures. We do so by explicitly accounting for the profit-driven motivation of the commercial entities and their mutual competition at service provision level.

3 SYSTEM MODEL

There are three main types of actors in our model in Fig. 1:

The *Community Network Infrastructure Provider (CNIP)* combines the roles of PIP and NP, as in cases *a* and *CN* in Fig. 2. It corresponds to the small group of people who initiate and typically operate the CN. They are often organized as a non-profit entity and their main task is to ensure the sustainable funding of the effort.

The *end users* are community members who contribute to the CN with their own equipment, assisting with its growth. They do so, to get access to the Internet services of one of the Internet Service Providers that operate over the CN. Their population N is taken equal to the maximum possible subscriber units out of the community; for instance, they could correspond to households.

The *(Internet access) service providers (SPs)*. These entities offer Internet access over the CN infrastructure, maintaining customer relationships with the end users.

3.1 Network infrastructure deployment

The network infrastructure deployment proceeds in two distinct phases.

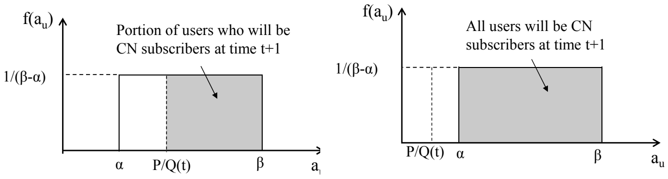
3.1.1 The initial investment by the CNIP. First, the CNIP invests an amount c_0 in the network, to purchase equipment and set up the first network nodes including labor expenses. This investment lets the CNIP cover a particular geographical area. The actual geographical coverage of the deployed network is a non-decreasing function $I(c_0)$ of the invested amount and relates directly to the number of users N_0 the network can originally reach (*market size*); namely, $N_0 = f(I(c_0))$. To keep the model tractable, we adopt the *uniform user distribution assumption*, demanding that the portion of the users covered by the CN equals the normalized geographical coverage $Q \in [0, 1]$ so that

$$Q_0 = N_0(c_0)/N = g(c_0) \tag{1}$$

where $g(\cdot) \equiv f(I(\cdot))$.

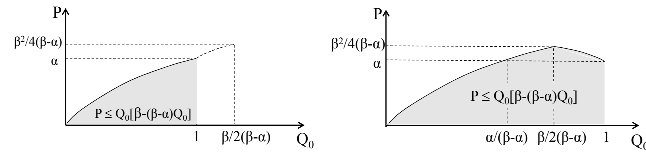
3.1.2 The crowdsourced CN growth process. Then, over a longer-lasting phase, end users join the network contributing their own equipment and the community network can grow much larger than the original investment allowed. On the other hand, in many cases a CN follows a path towards extinction, if the interest of users in it, including those forming the CNIP team, fades away with time.

These two scenarios for the CN evolution over time are captured by the simple model in [18]. Therein, the CN evolution process is approached as a repeated user-level decision problem. The community members iterate over time on joining the CN, if they have not done so, or maintaining their subscription to it, if they have already joined earlier. Their decision is driven by two factors: the time-varying network coverage $Q(t)$ and a price signal P. For a single SP, this would be the subscription fee itself; for M SPs, it could be a function $f(\mathbf{p})$ of the subscription fee vector $\mathbf{p} = (p_1, p_2, .., p_M)$, *e.g.*, its minimum or average. Namely, a user u is part of the CN at time t and gets Internet access service from one of the SPs, as far



a. $\alpha \leq P/Q(t) < \beta$ b. $P/Q(t) < \alpha$

Figure 3: Evolution of CN coverage at time t+1, depending on the network coverage at time t, $Q(t)$, and the price signal P. When $P/Q(t) > \beta$, no users will be CN subscribers by time $t+1$.



a. $\beta \leq 2\alpha$ b. $\beta > 2\alpha$

Figure 4: Feasible combinations (shaded area) of (P, Q_0) values ensuring non-zero steady-state CN coverage, according to the model in [18]. The respective subscription fee and initial investment amount depend on the spread of the user preferences (*i.e.*, parameters α and β and their ratio).

as the net value

$$v_u = a_u \cdot Q(t) - P \tag{2}$$

she extracts from it is non-negative. The user-specific factor a_u differentiates users with respect to how they weigh the CN coverage and the subscription fees in their decisions. For given network coverage, higher a_u values imply readiness to pay more for the Internet access service.

As users add/remove their own nodes to/from the CN, the CN coverage, both geographically and in terms of actual network users, follows a different trajectory in time. When the a_u factors follow a uniform distribution $U[\alpha, \beta]$, the instantaneous CN coverage is given by

$$Q(t) = \frac{1}{\beta - \alpha}[\beta - \min(\max(\alpha, \frac{P}{Q(t-1)}), \beta)] \tag{3}$$

and shown in Fig. 3. Depending on the values of α and β, the price signal P and the initial CN coverage Q_0, the network evolves towards a different steady-state coverage, Q_e. We refer the interested reader to [18] for the detailed analysis of this model; herein, we summarize its main findings that are relevant to our model:

- when $\beta \leq 2 \cdot \alpha$, $Q_e = 0$ if $P > \alpha$, irrespective of the initial coverage Q_0, while $Q_e = 1$ for
$$P \leq Q_0 \cdot (\beta - (\beta - \alpha) \cdot Q_0) \tag{4}$$
Hence, the CN expands to full coverage as far as P remains below an increasing function of the initial coverage (4); otherwise, it dies out. The higher the initial CN coverage, hence the initial investment in network infrastructure, the higher the fees that can be charged by the SPs, without inhibiting the evolution of the CN coverage towards $Q_e = 1$.
- when $\beta > 2 \cdot \alpha$, there is more flexibility in the Q_0 *vs.* P trade-off in (4). Now, $Q_e = 1$ as far as $P \leq \alpha$, but the CN can also reach a steady-state coverage
$$Q_e = Q_s = \frac{\beta + \sqrt{\beta^2 - 4 \cdot (\beta - \alpha) \cdot P}}{2 \cdot (\beta - \alpha)} < 1 \tag{5}$$
when higher fees
$$\alpha < P \leq \frac{\beta^2}{4(\beta - \alpha)} \tag{6}$$
are charged.

The two cases are shown in Fig. 4.

The CNIP makes the CN infrastructure available to different SPs that charge customers for their services. In return, it gets a part h of the monthly fee as a commission for the infrastructure use. Furthermore, the CNIP enters peering agreements with one or more transit ISPs, which interconnect its network with the Internet. It undertakes the cost of leased line(s) and recovers it from the SPs that use its network infrastructure (see section 3.3).

3.2 Service provision and actor profits

Let $\mathcal{M}$ be the set of service providers, with $M = |\mathcal{M}|$. They offer services to the end users and maintain customer relationships with them. In this work, we consider M SPs providing the same service, Internet access connectivity.

SP_i charges a monthly subscription fee p_i for its services. The fees that are chosen by the SPs have an impact on both the overall number of customers they will attract as a whole (portion Q_e of market), and their individual customer shares

$$N_i = r_i(N, w_1 p_1, w_2 p_2, .., w_i p_i, .., w_M p_M) \equiv r_i(\mathbf{p}; N, \mathbf{w}) \tag{7}$$

where r_i is a monotonically decreasing function of the charged fee p_i and the vector of weights $\mathbf{w} = (w_1, w_2, .., w_M)$ essentially summarize how SPs score beyond the fee criterion. For instance, the fee charged by a less reliable SP or one with worse brand name (*e.g.*, due to slow response to customer requests) would be given a higher weight, which make this SP look more "expensive" than it actually is. An example of such a function is the normalized exponential function

$$r_i(\mathbf{p}; N, \mathbf{w}) \doteq \frac{N \cdot Q_e}{1 + \sum_{j \in \mathcal{M} \setminus i} e^{(w_i p_i - w_j p_j)}} \tag{8}$$

The numerator of (8) equals the portion of the potential customers N that subscribe to the Internet access service overall through any of the M SPs (effective market size). The inverse of the denominator expresses the effective market share of SP_i (a number in [0,1]).

Hence, the net profit of the CNIP is

$$u_0(c_0, \mathbf{p}) = h \cdot \sum_{i=1}^{M} N_i \cdot p_i - \frac{c_0}{d} \tag{9}$$

where d amortizes the investment cost c_0 over a number of months[1].

The revenue of SP_i equals $N_i \cdot (1-h) \cdot p_i$, after accounting for the commission h of the CNIP for the operation and maintenance of the shared network infrastructure.

On the other hand, SP_i undertakes a part c_i of the cost of the leased line(s) that connect the shared network infrastructure to the Internet, as described in section 3.3. Hence, the net profit of SP_i out of the shared network infrastructure is

$$u_i(p_i) = (1-h) \cdot N_i \cdot p_i - c_i, \; i \in \mathcal{M} \tag{10}$$

3.3 Cost-sharing rule

One of the responsibilities of the CNIP is to buy Internet transit connectivity from one or more transit ISPs and implement a cost-sharing rule for distributing the Internet transit costs. This implies that the CNIP measures how much transit traffic[2] is generated by the customers of each SP and computes a cost share for it accordingly.

Formally, let $C(q)$ be the cost function for total Internet transit traffic q produced by the customers of all M SPs, with $C(0) = 0$. If q_i is the traffic share produced by the customers of SP_i and $\mathbf{q} = (q_1, q_2, .., q_M)$ the overall network traffic profile, then a cost-sharing rule associates to each $(C(\cdot), M, \mathbf{q})$-tuple a vector $(c_1^M, c_2^M, .., c_M^M)$. Denoting the cost share of SP_i for traffic profile $\mathbf{q}$ and cost function $C(\cdot)$ with $c_i^M(C;\mathbf{q})$, the cost share of SP_i is given by the average cost pricing (ACP) rule [20]

$$c_i^M(C;\mathbf{q}) = \frac{q_i}{\sum_{j=1}^M q_j} C(\sum_{j=1}^M q_j) \tag{11}$$

Hence, the cost shares of SPs stand in proportion to the traffic their customers generate. An important advantage of the ACP rule is its resilience to manipulations of the merge-split type: the total charge for an SP remains the same, even if it finds ways to split its traffic into smaller parts, *e.g.*, by spinning off more virtual entities, or to merge its traffic with another SP, *e.g.*, by setting up a joint entity.

4 THE CROWDSOURCED NETWORK INFRASTRUCTURE SHARING GAME

In Section 3, we analyzed the different actors and their stakes in this layered network model, where the network infrastructure is owned *in common* by many community members, it is operated by one CNIP entity, and it is shared by many SPs providing services over it to end users.

The ultimate profit (or loss) of the CNIP and the SPs out of this layered network model depend on the original investment c_0 of the CNIP on network infrastructure, the pricing strategies of the SPs (pricing vector $\mathbf{p}$) and the cost-sharing rule that determines how the operational costs of the infrastructure are shared among the SPs. SPs need to compete against each other for attracting end users as customers but should also coordinate with the CNIP in generating a market large enough to render this business model profitable for all of them.

We capture the strategic interactions of the actors within the framework of leader-follower games. The leader player in our case is the CNIP that invests an amount c_0 in network infrastructure. This investment determines the initial network coverage Q_0 but this may grow or shrink to a different value Q_e, as discussed in section 3.1. The product $N \times Q_e$ is the *potential customer base*. The follower players are the M SPs. The charged service subscription fees determine the *actual customer base*, the customer shares of individual SPs and, for given cost-sharing rule, the net profit of the SPs (10) and the CNIP (9).

4.1 The SP pricing game

For a given choice of the c_0 value invested by CNIP, the choice of service subscription fees by SPs gives rise to the strategic-form game $G_M(c_0) = \langle \mathcal{M}, (p_i)_{i \in \mathcal{M}}, (u_i)_{i \in \mathcal{M}} \rangle$ where:

- $\mathcal{M}$ is the set of player-SPs;
- $(p_i)_{i \in \mathcal{M}}$ are the sets of strategies of the M SPs; and
- u_i is the payoff function for SP_i, as given by (10).

$G_M(c_0)$ is a continuous game; Nash Equilibria (NE) strategies can be found at the intersection of the best response functions of the M SPs. To find them, we maximize the payoff function u_i of each SP_i with respect to its own strategy p_i. Therefore, by first-order optimality conditions, we get:

$$\frac{\partial u_i}{\partial p_i} = (1-h)\frac{\partial N_i(c_0, p_i, p_{-i})p_i}{\partial p_i} - \frac{\partial c_i^M(c_0, p_i, p_{-i})}{\partial p_i} = 0, \; i \in \mathcal{M} \tag{12}$$

where we have explicated the dependence of both customer shares N_i and cost shares c_i on the fee values and the CNIP investment, and p_{-i} denotes the set of subscription fees of all SPs apart from SP_i.

4.2 The initial investment decision by the CNIP

If $\mathbf{p}(c_0)$ are the fee values that result from the system of equations (12), the CNIP would seek to maximize its net profit by solving the following optimization problem

$$\begin{aligned} \max_{c_0} \quad & u_0(c_0, \mathbf{p}(c_0)) \\ s.t. \quad & (4) - (12) \qquad\qquad (OPT) \\ & c_0 \geq 0, \; p_i > 0, \; i \in [1..M] \end{aligned}$$

where the net profit u_0 of the CNIP is given by (9).

(OPT) is a sigmoid optimization problem, sigmoid functions appearing both at the objective and constraint functions. Hence, the analytical characterization of the game equilibria (*i.e.*, existence and uniqueness) is non-trivial. Instead, we compute equilibria numerically.

Example: Two Service Providers

As an example, we consider the sharing of the CN infrastructure by 2 SPs under a concave cost function $C(q) = c \cdot log(q)$. The CN user shares captured by SP_1 and SP_2 are:

$$N_1 = \frac{N \cdot Q_e}{1 + e^{w_1 p_1 - w_2 p_2}}, \; N_2 = \frac{N \cdot Q_e}{1 + e^{w_2 p_2 - w_1 p_1}} \tag{13}$$

[1] Typically, this would be the period of network operation before serious infrastructure upgrades are needed; or the desired recuperation time of the investment.

[2] It is expected that CNIPs will operate Internet Exchange Points (IXPs) for serving traffic between the SPs that use its infrastructure so that this traffic does not contribute to the cost. Nothing changes from modeling point of view if this traffic is also accounted for in the operational cost.

where Q_e is a function of the initial investment c_0 by the CNIP, see (1).

If q_{av} is the average user traffic per month, the transit connectivity cost shares of the two SPs, see (11), become

$$c_1^2 = \frac{C(NQ_e \cdot q_{av})}{1 + e^{w_1 p_1 - w_2 p_2}},\ c_2^2 = \frac{C(NQ_e \cdot q_{av})}{1 + e^{w_2 p_2 - w_1 p_1}} \quad (14)$$

Combining (10) with (13) and (14), the payoff functions of the two SPs can be written:

$$u_1 = \frac{(1-h)NQ_e p_1 - cQ_e log(NQ_e q_{av})}{1 + e^{w_1 p_1 - w_2 p_2}}$$
$$u_2 = \frac{(1-h)NQ_e p_2 - cQ_e log(NQ_e q_{av})}{1 + e^{w_2 p_2 - w_1 p_1}}$$

Note that, in the general case, Q_e: a) depends on the subscription fees p_1 and p_2 through the price signal $P = f(p_1, p_2)$ and according to what is described in section 3.1.2 and equations (4)-(6); b) is a discrete function of (c_0, p_1, p_2), taking values in $\{0, Q_s, 1\}$. However, we can branch the analysis depending on the support set of the a_u distribution, *i.e.*, parameters α and β:

- when $\beta \leq 2\alpha$, we can set $Q_e = 1$ under the additional constraints (4) and $P \leq \alpha$;
- when $\beta > 2\alpha$, we can set $Q_e = Q_s$ after (5), under the additional constraints (4) and $\alpha < P \leq \frac{\beta^2}{4(\beta-\alpha)}$; or set $Q_e = 1$, under the additional constraints (4) and $\alpha \geq P$.

For instance, in the first case, applying the first-order optimality conditions in (12) and defining

$$\gamma = e^{w_1 p_1 - w_2 p_2},\ P = (p_1 + p_2)/2 \quad (15)$$

we get the two equations that NE values of p_1 and p_2 must be satisfying:

$$(1-h)N[1 + \gamma(1 - w_1 p_1)] + c\gamma w_1 log(Nq_{av}) = 0$$
$$(1-h)N\gamma(1 + \gamma - w_2 p_2) + cw_2 log(Nq_{av}) = 0 \quad (16)$$

In turn, the optimization problem faced by the CNIP entity becomes

$$\max_{c_0} \quad \frac{Nh}{1+\gamma} \cdot (p_1(c_0) + \gamma p_2(c_0)) - \frac{c_0}{d} \quad (17)$$
$$s.t. \quad (4), (15), (16)$$
$$c_0 \geq 0,\ p_i > 0,\ i \in [1..M]$$

This is a non-linear continuous optimization problem that can be solved with numerical techniques.

5 MODEL EVALUATION AND IMPLICATIONS

5.1 Methodology and model input data

Our model requires the following four inputs:

- The network deployment area and its population, which determines the size of the targeted user base (potential "market") N and the way they are spread over this area.
- The dependence of the initial coverage of the CN on the investment c_0 made by the CNO, *i.e.*, the function $g(c_0)$ in Eq. (1). The coverage is measured in both geographic terms and, in light of the uniform user distribution assumption in (1), in terms of actual CN subscribers.

Table 1: Network deployment area type and building density in the selected scenarios.

Scenario-Abbrv.	Buildings	km^2	Buildings/km^2
Pred. Urban - PU	43853	102	429
Intermediate - IM	6663	45	148
Pred. Rural close to a city - PRC	2052	34	60
Pred. Rural remote - PRR	4414	182	24

- The Internet transit cost, *i.e.*, the cost of the line leased by the CNO, as a function of its capacity. This corresponds to the function $C(q)$ introduced in section 3.3.
- Estimates of the average user traffic demand q_{av}. This determines the aggregate expected load q out of a given number of users and, eventually, the required capacity of the line(s) that have to be leased.

In what follows, we describe how we parameterize these inputs out of real data.

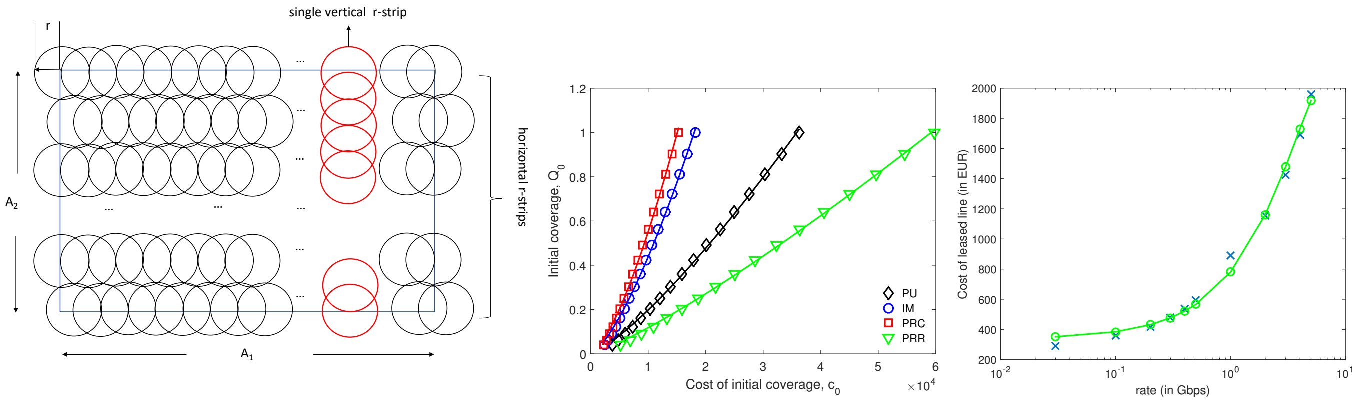
5.1.1 Network deployment area. We have chosen to consider four specific areas from the province of Tuscany in Italy, for which Open Data about their population density could be easily made available[3]. The four areas map one-to-one to the four distinct territorial classes defined in the OECD (Organisation for Economic Co-operation and Development) classification standard for regions worldwide [22]. The standard classifies regions into "predominantly urban (PU)", "intermediate (IN)", "predominantly rural regions close to a city (PRC)" and "predominantly rural remote regions (PRR)", according to their population density, the percentage of the regional population living in an urban center, and "the driving time necessary for a certain share of the regional population to reach an urban center with at least 50 000 people". The four areas are listed in Table 1 along with their geographical span and the buildings' count/density.

In our analysis, we assume that the effective market size N coincides with the number of buildings[4]. We also use the area size figures (third column) to relate the investment of the CNIP to the achieved coverage, as described in section 5.1.2.

5.1.2 Initial CN coverage vs. initial CNIP investment. The initial investment made by the CNIP relates directly to the number of nodes it will set up to instantiate the CN. Each node installation includes the cost of the required wireless devices plus mounting hardware costs. Typical wireless devices used for this purpose together with their main features (transmission range, cost, coverage characteristics) are listed in Table 2, while the mounting hardware costs are analyzed in [2].

Formally, the CNIP seeks to minimize the initial investment cost, that is, the number of installed nodes, that achieve a given target

[3]In fact, the available Open Data goes in far more detail including (a) street maps with building shapes that could be extracted from OpenStreetMap (https://www.openstreetmap.org) and other open repositories maintained by public administrations, in particular for rural areas; (b) LIDAR (Light Detection and Ranging) traces about building heights that are also made increasingly available by public administrations. For our evaluation, building (population) density data suffice.
[4]This is clearly a first-order approximation to simplify the derivation of the market size. A more elaborate analysis could take advantage of detailed census data. The collection and analysis of such data makes sense by CNIP entities but is only marginal for the assessment of the infrastructure sharing model in this paper.



(a) (b) (c)

Figure 5: Parameterizing the model with real data: (a) Emulating the node placement pattern in [16] for covering the area A_1 x A_2 with r-strips of r-disks each, while ensuring connectivity between nodes at the centers of these disks; (b) Fitting the function $g(x_0)$ in the three scenarios for the four areas of network deployment in Table 2; (c) Fitting the $C(q)$ function for the cost of the leased line.

Table 2: Technical specifications of typical wireless mesh networking devices (Figures are drawn from the site of a popular manufacturer for the MCS9 Modulation and Coding Scheme).

Name	Avg. Price (EUR)	Beamwidth (H,V) (degrees ^{0})	Transmission range (Km)
ISO90	200	90,30	1.34
ISO45	112	45,45	1.34
LB	73	20,10	3.79
NB	100	30,30	2.39
NS	134	60,20	1.69

coverage $Q_0 \leq 1$, while they are connected with each other and the Internet gateway node(s). This problem is reminiscent of the *connected sensor coverage* problem (CSCP) that emerges in wireless sensor networks. In CSCP, the aim is to place a minimum set of sensors S_c over an area A to collectively cover a target sensing area, which can be generally different than A, while they form a single connected component. The problem exhibits different variants depending on whether the possible locations of the sensor nodes are fixed (*e.g.*, [13]) or not (*e.g.*, [16]) and whether every part of the sensing area must be covered by one or more sensors [25].

In a wireless CN, as with the sensor networks, the nodes are deployed so that they remain connected with each other while covering a target area. In this case, "coverage" denotes the availability of adequate radio signal quality that allows any node in the given area to attach to the CN. In general, the coverage area of a node may take different shapes depending on the radio propagation environment and the node transmission power levels. However, since we only need an estimate for the number of nodes needed to cover a given area, we can approximate them as r-disks (see Fig. 5(a) and refer to the analysis in [16] for the CSCP. Based on that analysis, it can be shown that to get a connected full cover of a rectangular area of size $A_1 \cdot A_2$ it suffices to place $A_2/r+1$ *r-strips* of $A_1/r+1$ nodes plus one strip of $A_2/r+1$ nodes, where an r-strip is defined as a string of r-disks placed along a line so that the centers of two adjacent disks lie at distance r from each other. Overall, the required number of nodes (r-disks) is

$$N_0(A_1, A_2; r) = (\frac{A_2}{r} + 1) \cdot (\frac{A_1}{r} + 2) \tag{18}$$

Hence, to estimate the cost needed to cover an area $S\ km^2$ (third column of Table 1), we take the following steps:

- First, for a given device d (first column in Table 2) and its transmission range r_d (fourth column in Table 2), we estimate, through (18), how many nodes $N_0(\sqrt{S}, \sqrt{S}; r_d)$ fully cover the area. The coverage of each of these nodes is omnidirectional, *i.e.*, it can be viewed as an r_d-disk.
- Then, we check the third column in Table 2 to find out how many devices n_d with the given radiation patterns make up one "node" of omnidirectional coverage. For example, we would need to co-locate in each installation location four ISO90 devices with sectorial coverage of 90 degrees to get one node of omnidirectional coverage.
- Finally, we compute the respective cost as

$$c_0(A, d) = n_d \cdot N_0(A, A; r_d) \cdot prc_d \tag{19}$$

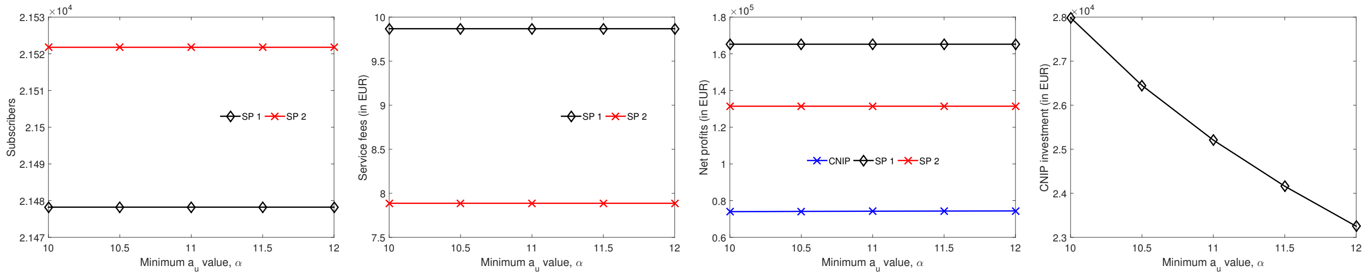
where prc_d stands for the price of the chosen device, as reported in the second column of Table 2.

To derive an analytic expression for $g(c_0)$, let S be the area that we need to cover to let every household join the CN. If $Q_0 = A^2/S$ is the achieved normalized coverage with $N_0(A, A; r_d)$ nodes, we fit the distinct pairs $(c_0(A, d), Q_0)$ with a continuous curve of the type

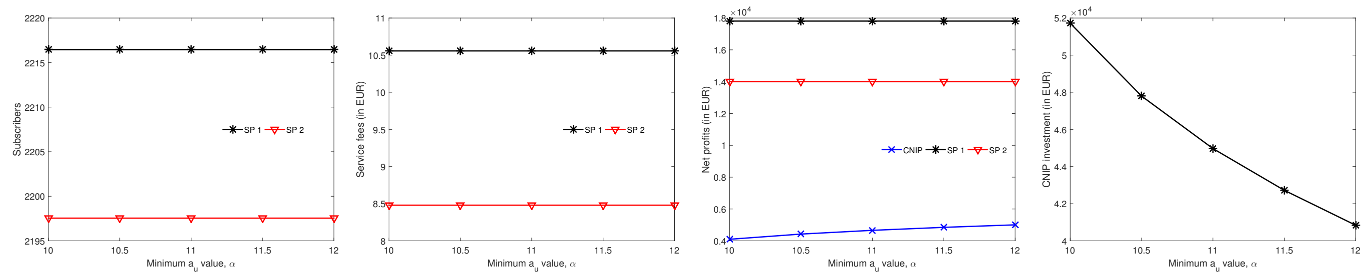
$$Q_0 = g(c_0) = (c_0(A, d)/a_0)^{b_0} \tag{20}$$

where a_0, b_0 are parameters estimated with the fitting process. Figure 5(b) plots the outcome of the fitting process for the four areas in Table 1.

5.1.3 Internet transit cost. For parameterizing the cost function $C(q)$ of the Internet transit, we have relied on pricing data from Xarxa Oberta, a connectivity provider owned by the Government



(a) Network deployment area - PU



(b) Network deployment area - PRR

Figure 6: Subscribers, subscription fees, net profits and initial investment needed by the CNIP at the equilibria of the game: $\beta = \alpha + 8$, $w_1 = 0.2$, $w_2 = 0.25$.

Table 3: Average traffic load per area type in the numerical scenarios.

Area type	ADSL 4	ADSL 24	Max traffic load (Mbps)	Estimated q_{av} (Mbps)
PU	42	715	345.4	0.478
IM	10	78	40	0.454
PRC	2	63	35	0.539

of Catalonia (*www.xarxaoberta.cat*). Its primary aim is to connect around 750 headquarter sites of the Catalonian government with a neutral optical fiber network. In parallel, excess network capacity is made available to the wholesale market for telecom operators. Xarxa Oberta serves as Internet Transit provider for the Catalan CN *guifi.net*, one of the largest community networks in Europe and worldwide [5]. In Figure 5(c), we have fitted these numbers with a truncated second-order polynomial function of q.

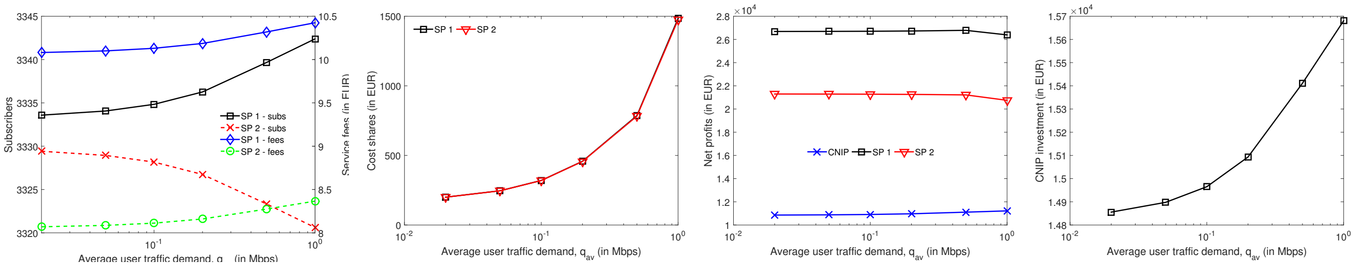
5.1.4 Average user traffic demand. We draw on data about the the hourly variation of aggregate Internet traffic over a week in December 2018. The data pertain to ADSL users, subscribers of 4MB and 24MB service, of a Greek operator in different types of areas (PU, IM, PRC). Table 3 reports the maximum evidenced traffic (busy hour) and the mix of ADSL users generating it. From that table, we get an estimate of q_{av} corresponding to the busy hour.

5.2 Numerical results

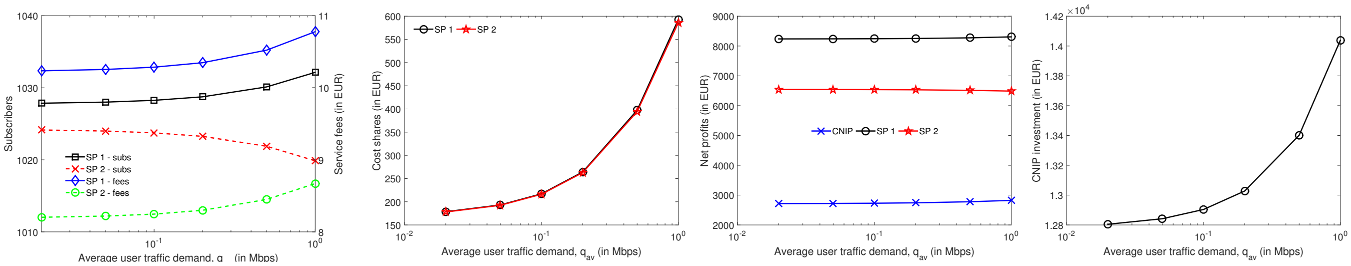
We compute numerically the game equilibrium states for the four network deployment areas in Table 1, in scenarios with two Internet Service Providers sharing the CN infrastructure. As default value, we assume a 20% commission of the CNIP for each CN user subscription to the SPs, *i.e.*, $h = 0.2$. In section 5.2.3, we look closer into the impact of h on the game outcome. The CNIP investment recuperation time d is taken to be 12 months, which appears to be a common assumption in literature (*e.g.*, [9]).

5.2.1 Impact of users' readiness to pay for given network coverage. In a first set of experiments, we vary the range of the a_u distribution in Fig. 3: we let its low end α slide over the interval [10,12], while the upper bound β is set to $\alpha+8$. The first remark out of Fig. 6 is that at the equilibrium states all three entities, the CNIP and the two SPs, show profits. This is a necessary condition for such synergies. The second remark is that having users that assign higher weight to the network connectivity (higher a_u values, hence ready to pay more for given network coverage) does not favor somehow the SPs: the subscription fees they can charge at the game equilibrium do not change (2nd column in Fig. 6) and the same holds for the revenue they can generate (3rd column in Fig. 6). On the contrary, the CNIP entity can save in the order of 15-20% on the initial investment it has to make to launch the CN. As users are ready to pay more for given connectivity, the CNIP can reduce the initial 'seed' coverage and the CN still evolves to full coverage.

Besides the dependence on the community's willingness to pay for connectivity, the required upfront investment of the CNIP is strongly dependent on the area type of the network deployment. The amount that has to be invested is significantly higher for predominantly rural remote areas, where the population is far more sparsely distributed and its coverage demands more node installations (4th column in Fig. 6). Higher investment costs demand higher cash flow on the CNIP side, who might need to resort to loans or seek for public subsidies to ensure it. At the same time, the profit margins are smaller for the CNIP (3rd column in Fig. 6), confirming that connecting these areas is more challenging.



Network deployment area - IM



Network deployment area - PRC

Figure 7: Subscribers and subscription fees (leftmost plots), cost shares (second from left), net profits (second from right) and initial investment by the CNIP (rightmost plots) at the game equilibrium state: $\alpha = 10$, $\beta = 18$, $w_1 = 0.2$, $w_2 = 0.25$.

5.2.2 Impact of average user demand. In a second set of numerical experiments, we have varied the average user demand to test how the game dynamics change as user demands grow. Notably, the equilibrium subscription fees charged by SPs in Fig. 7 are quite robust to the demand scaling, increasing rather marginally (less than 0.5 EUR) as the average per user demand rises from 20kbps to 1Mbps. The implications of this trend are different for the three types of actors.

For the community members, it means that they can satisfy more demand practically at the same price. For the CNIP, the increase of fees results in a small yet visible increase of the initial investment it has make in the CN. This increase essentially makes up for those users who find the slightly increased fees prohibitive. Finally, the SPs do not really benefit from the slight increase of the fees since this is balnaced out by higher Internet transit costs (plots in the second column of Fig. 7).

Again, the trends are similar across the two area types (IM and PRC), although in absolute numbers, the more densely populated IM areas are more attractive for all actors (3rd column in Fig. 7).

5.2.3 Impact of the CNIP commission. One critical parameter in the way profits are split between all actors is the commission h applied by the CNIP on the revenues of SPs. Figure 8 demonstrates that the split of revenues among the three entities at the equilibrium may vary considerably as a function of h. IN principle, the CNIP has the option to adopt a more aggressive policy, imposing a higher commission h, but given that it is typically a non-profit initiative, it will seek to set h to a value that compromises two requirements: the coverage of all expenses related to network maintenance and operation, on the one hand, and the engagement of the SPs into the CN, on the other. Both of them are of paramount importance for ensuring the sustainability of the network and preserving the community's rights to Internet access.

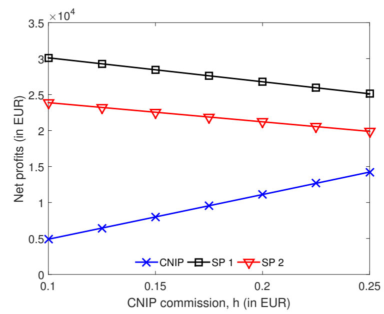


Figure 8: Impact of CNIP commission h on the net profits of all three entities: IM area, α=10, β=18

6 CONCLUSIONS

Ambitious plans for ubiquitous broadband connectivity have not yet given convincing answers as to how these plans will be funded, in particular, in areas (rural, sparsely populated) that are not attractive in pure market terms. Policy makers increasingly iterate on alternative business plans that could engage more stakeholders in the network infrastructure deployment process and distribute the respective investment costs.

We have looked into one of these alternative plans, whereby the network infrastructure is built bottom-up with crowdsourcing practices and managed as commons by a Community Network Infrastructure Provider, while Internet services are provided on top of it by commercial service providers. We have formulated and analyzed the interactions between those actors as a leader-follower game, drawing positive conclusions and instructive hints about the sustainability of such synergies.

The proposed model is by no way exhaustive. There are several directions to expand/detail it further at the expense of complexity and tractability. For instance, end users could consider the spatial distribution of network coverage and how well it matches their own mobility and network access patterns when deciding whether to join the CN or not (*e.g.*, see [3]). Likewise, the offer of service plans from the SPs could be richer with more elaborate pricing plans. Nevertheless, we tried to capture the main characteristics of the actors' interactions while keeping it tractable and populating its parameters with real data to the maximum possible extent.

Finally, although our work provides evidence for the feasibility of synergies between communities and for-profit service providers in technical terms, their ultimate realization will depend on provisions made in many other fronts, not least at the regulatory and policy-making front [6].

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