Blockchain models for universal connectivity

Leandro Navarro[1,2], Ignacio Castro[3,2], Emmanouil Dimogerontakis[1],
Mennan Selimi[1], Arjuna Sathiaseelan[2], Felix Freitag[1], and Roger Baig[1,4]

[1] Universitat Politècnica de Catalunya, Barcelona
[2] Ammbr Research Labs, Cambridge, UK
[3] Queen Mary University of London, UK
[4] guifi.net Foundation, Catalunya

Abstract. Universal connectivity is still a dream for half of the global population, despite being used to provide crucial services and enable participation in societies around the world. Decentralised networking infrastructures create an opportunity for local entrepreneurship, mainly in underserved areas, where connectivity can expand incrementally and be sustainable through service fees obtained from the demand and consumption of services that compensate the cost of the services provided by network devices that mesh with each other. While the data flow is coordinated by routing decisions, the economic flows can be coordinated by blockchain transactions. Together, networking devices such as wireless mesh or fibre networks combined with Internet backhaul links from diverse suppliers can deliver Internet connectivity to nearby citizens. We discuss the characteristics of different service models, the technological opportunities of combining blockchain with mesh networks, the options for pricing and investment models, and inter-dependencies, validated in our case studies, laboratory and field experiments. We find that blockchain and mesh networking technologies combined enable decentralised models to bootstrap and scale-up crowdsourced networking services that aim to be socially and economically sustainable.

Keywords: blockchain, mesh networks, Internet universality

1 Introduction

There are currently around 4 billion people without Internet access according to ITU estimates [36]. Considering the wider role, the Internet plays today in providing access to crucial services like education, health, e-governance, social networks etc – enabling universal access to the Internet is a major challenge for all the stakeholders involved in the business of Internet access provisioning. With well known organisations such as the Internet Society (ISOC) and the Association for Progressive Communications (APC), leading several initiatives (e.g supporting the creation of Internet eXchange Points (IXPs), community networks), several other initiatives have also recently sprung up such as the Internet.org, Google balloon, Microsoft TVWS projects in America, Asia and Africa, etc. – all spearheading efforts in enabling wider community connectivity across rural and emerging markets. These initiatives are addressing the connectivity problem through the use of several access technologies (last mile, middle mile, core), provisioning regional transit and caching infrastructures, as well as exploring solutions to address the socio-economic sustainability problem in rural and emerging markets.

From the technical perspective, significant advances in the licensed and unlicensed wireless such as the 4G (hundreds of Mbps), 5G IEEE 802.11ac (around Gigabit) and 6G (above 1Gbps) IEEE 802.11ax or 802.11ah, position unlicensed wireless as key technology for solving the last mile (user device - access network) access problem.

Considering the massive opportunity of the billions of unconnected or underserved, mesh network technology has the potential to solve the accessibility problem as evidenced by successful community network initiatives across the world [26]. A mesh network is a network topology in which each node (routers) is capable of relaying data for others. In mesh networks, all nodes cooperate in the distribution of data throughout the network to the mutual benefit of its participants. With each participating node, the reach, throughput and resilience of the network expands. An ad-hoc mesh network allows public participants to join without prior authorisation or setup. When powered on, a wireless mesh network node scans the radio spectrum to identify other nodes it can connect to. Once connected, the node benefits from the connectivity of others while also extending the reach of the network for every other participant. With sufficient benefits to participation, an ad-hoc mesh network can quickly grow to provide shared connectivity in many locations on a global scale and at a much cheaper rate than a centralised topology [22]. While promising, the missing ingredient for widespread adoption has always been the issue of economic sustainability and scalability.

Networking services in underserved areas are an opportunity of self-provision as alternatives to the large-centralised telecom providers that have not shown interest or profitability in these areas [34]. Self-investment, decentralization, the homemade model [23] creates opportunities for local entrepreneurship that results in keeping local value locally, instead of extracting value from already deprived economies. Mesh access networks, sharing internet access, local services, bring not only connectivity and digital services but also contribute to local socio-economic development. Opportunities for local investment create local social and economic benefits, and contribute to the sustainability of local markets, creating sources of income, jobs, and surpluses that tend to be reinvested locally instead of being sent back to remote richer areas. Fintech [16] technologies such as blockchain, smart contracts for trust, digital currencies or token payments and compensation mechanisms are enablers for the exchange of value that appears in decentralised networks that can develop in these underserved areas. These economic flows can not only run in the local network, but also expand to other local sectors, and feed the local economy, but can also run globally, enabling incoming and outgoing value flows that could be used to inject or extract value, with the potential of major effects, positive or negative, in a given locality.

The main contribution of this paper is the analysis of opportunities, options and characteristics for decentralised and self-organised networks that combine mesh networks with blockchain-based economies and contracts.

We start in Section 2 by looking at the organisational side of networking services, outlining the range of organisational and governance models for network infrastructures. Section 3 analyses the technological opportunities and challenges for decentralisation, looking at mesh and blockchain. Section 4 discusses about the participation side of service consumption (usage), pricing and investment (construction) models for these networks. Section 5 discusses the intersection and how decentralised data and money flows enable decentralised organisational models, with the challenges and opportunities to deal with participation, growth, variability, and sustainability. We conclude with the related work and conclusions.

2   Organizational and governance models for network infrastructures

Network infrastructures produce the connectivity that people require to be online. This service can be developed according to different organisational models, with different conditions to the participants as producers or consumers, which result in choices on the supporting economic/business models. Some of the relevant types of network infrastructures:

– **The Internet**, the global system of interconnected computer networks that use the Internet protocol suite (TCP/IP) to link devices worldwide, is a decentralized federation of coordinated networks. The governance is based on a set of local and global institutions that define common terms, and its sustainability depends on an ecosystem that exchanges data traffic and economic compensations that includes all the other remaining models.

– **IXPs** are physical interconnection facilities enabling networks to establish peering connections between each other. Benefiting from economies of scale, these facilities have substantially reduced the costs of peering interconnections, which have subsequently resulted in a huge number of such connections. Accompanying such growth, the number of IXPs has tripled in the last decade. Despite of the homogeneity of the service they provide, there are different models of governance and financing of this facilities. IXPs in Europe have typically pursued a more cooperative model where the IXP operates as a non-for profit organisation, sometimes with the members as the stakeholders of the facility. Differently, US IXPs are frequently commercial for-profit organisations. As European IXPs succeeded in terms of traffic volumes, number of members and impact on transit prices in comparison to the US, these IXPs have extended their model beyond Europe [10, 7][5]. While different models of governance have economic implications on how these facilities are funded and the financial contributions of the members, the latter typically pay for port capacity and membership, regardless of whether it is a for-profit IXP or not. Differently, US-based IXPs frequently see in the co-location a business opportunity making it the centrepiece of its business.

– **Community Networks** (CNs) are IP-based networks built, owned, and operated by citizens in a participatory and open manner. Therefore they are networking infrastructure managed as open commons (cooperative, and oriented to deliver connectivity to individuals –retail– at a reduced cost). Hundreds of CNs operate across the globe in rural and urban as well as rich and poor areas. In these communities, the participants, including volunteers, enterprises, and public or private organisations share not only networking hardware but also time, effort, and knowledge. In Europe, several CNs have been operating for more than a decade and have several thousands of nodes.[6]

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[5] Bandwidth costs: `https://blog.cloudflare.com/bandwidth-costs-around-the-world/`. Worth noting are also the IXPs ecosystems of Brazil (IX.br, formerly PTT) and Argentina (CABASE), fostered by the government and a trade association of Internet Service Providers (ISPs)–respectively, successfully created a national network of IXPs

[6] These infrastructure use any available technology, such as fibre and unlicensed or licensed wireless. For example, Freifunk (`http://freifunk.net`) in Germany and guifi.net (`http://guifi.net`) in Spain both have over 35,000 nodes (2018). In Mexico, community-owned and operated wireless GSM networks serve thousands of people in more than 20 indigenous municipalities (`https://www.rhizomatica.org/`). In South Africa, local ISPs are being created over a similar structure, the Zenzeleni.net cooperative (`http://zenzeleni.net/`).

CNs have been identified as one of the models for contributing to connecting the next billions [1] of people still unconnected or underserved.

The business model is based on crowdfunding, cost-oriented cooperative sharing of CAPEX and OPEX costs, and compensation across participants of investments and resource consumption, similar to IXPs but involving individual citizens.

– **Municipal networks** are network infrastructures provided either fully or partially by local governments, therefore with public presence, oriented to cost-recovery, and sometimes with public investment. Municipal networks focus on maximising connectivity from public (municipal) interest point of view, given the multiplying benefits of connectivity for society. They usually rely on public-private partnerships. The service is defined and governed by the public partner but implemented and operated by one or multiple private partners. Typical examples are the optical fiber service from Stokab[7] in the Stockholm region, among several other regions in Europe, or the public WiFi services in most European cities, which can follow diverse models for service provision as the public entity just defines, funds and oversees the public service under private operation.

– **Commercial ISP operators** are networks providing Internet access to final users so called *eyeballs*. They can cover large areas such as a country, small regions or populations such as with Wireless Internet Service Providers (WISPs) in rural areas, or provide mobile access including a spectrum license. ISPs interconnect with other networks to attain end-to-end connectivity. In order to do so they typically rely on two types of interconnections, transit and peering. Whereas in the former an ISP pays to another network for connectivity, in the latter two networks, peer, exchanging the traffic of each other's customers (and the customers' of their customers), for free or a fee. As end-users are unlikely to change of Internet provider very dynamically –either because of lack of choices or because it is a cumbersome process–, ISPs can have a great deal of control on both settling Internet access prices for end-users and interconnection with other content providers. ISPs are however rather heterogeneous in terms of the services they provide and their interconnection policy. For example, some ISPs can have a multiple role as ISPs, content providers and transit provision. The nature of the business of ISPs has a great impact on how they charge end-users. For example, an ISP that has its own content might see fit to favour, an ISP that also provides transit is likely to prefer receiving content through its own backbone[8]. The multiplicity of roles of ISPs and the bargaining power that they derive from them has been at the heart of the neutrality debate.

– **Crowdsharing operators**: The lack of connectivity can be partially solved in places where there is already a service infrastructure that can be open to more users. This is the case of the Eduroam for educational institutions or the Fon models for households. Eduroam is a secure, world-wide roaming access service developed for the international research and education community. Eduroam allows students, researchers and staff from participating institutions to obtain Internet connectivity across campus and when visiting other participating institutions by simply opening their laptop[9],

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[7] `https://www.stokab.se/`

[8] In the extreme, an ISP that is also a Tier 1 network –provider-free networks that peer with each other and provide global Internet reachability– has a huge negotiating power when dealing with content providers that will ultimately depend on T1s networks to reach the eyeballs if they fail to interconnect directly with the ISP.

[9] `https://www.eduroam.org/what-is-eduroam/`

thanks to a federated authentication service. Fon[10] is a WiFi provision service that allows individuals, referred to as Foneros, to provide WiFi access by sharing their home Internet connections and gain access to free WiFi at other locations. Therefore both constitute a decentralised WiFi Access Point service. This model is not about expanding the geographic coverage of a network infrastructure, but about providing and reselling WiFi-based Internet access to more clients from existing network locations.

– **Provider sponsored** such as Free Basics, an initiative backed by Facebook (Internet.org) to provide users in developing countries free mobile Internet access to selected services in partnership with mobile (cellular) service providers in these regions around the world. Another case are content distribution networks (CDN) that bring content and services to the access network, reducing or eliminating the transit cost to reach it. The sponsor covers the cost of such connectivity as the benefits provided by that access or usage of certain services compensate the costs and contribute to bring more value to the provider.

These models differ in the structure of participation, centralised in commercial ISPs and provider sponsored, or decentralised and disintermediated with common cooperative coordination in CN, some IXPs, and crowdsharing; in the type of participants, with an undifferentiated and open model in CNs, IXPs, or a separation between providers and consumers in the rest; in the provision of services, only by the "owner" (vertical integration) or by any allowed participant, including externals (so called "end-to-end" or "Over-The-Top" services); in the investment, managed centrally or funded by some or all the participants; in the economic profit, extracted from consumers by an external provider, or spread across the participants; in who pays, either the beneficiary, that can be the consumer, or content providers such as Facebook, as well as universities, libraries or municipalities.

3 Technological opportunities and challenges for decentralization: Mesh and Blockchain

Blockchain technologies and related technological developments bring not only opportunities but also challenges to organise and implement decentralised, scalable and sustainable universal connectivity solutions. However, technology is not neutral and they are developed with a bias towards specific business and governance models.

Decentralization: While some networking technologies bring about centralised models (operators) such as cellular access networks, TDMA/FDMA based, with a centrally planned (capacity and coverage) network with local services and an Internet gateway, other technologies allow decentralised models (crowdsourcing): Wi-Fi access points, wireless mesh networks, multiple small Internet gateways that can be aggregated. A centrally planned network is not required, which brings about the need for incentive mechanisms to provide the necessary capacity and coverage.

Similarly, in terms of financial technology (fintech), some options bring about centralised models (providers such as banks, notaries, payment processors), while other technology choices enable decentralisation, such as blockchains, with digital identities, claims, tokens and smart contracts that enable direct peer transfers or crowdfunding investment campaigns or smart contracts.

Sustainability: Decentralised networking combined with financial technologies allows building self-sustaining crowdsourced infrastructures that produce the connectivity
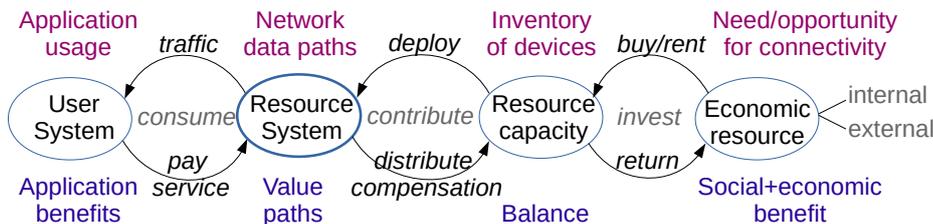
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[10] https://fon.com/

Fig. 1. Data and value flows: from need and opportunity (right) to usage (left).

and digital services that half of the global population still lack. Community networks and WISPs have shown the feasibility and effectiveness of bootstrapping networking infrastructures –using Wi-Fi access points and mesh networks, even cellular open base stations, shared Internet gateways– that can serve the needs for connectivity and digital services in areas where traditional operators have not shown interest due to lack or negative financial margins or have failed and abandoned.

Data and value flows combined: Although feasibility does not mean optimal scalability or profitability that, according to our experimentation and pilot deployments, can take place when combining networking and financial technologies together. Building blocks that combine decentralised data flows with economic flows, see Figure 1, allow the development and expansion of infrastructures and services that are balanced and scalable, and that mesh both in terms of fluid data and economic exchanges. These building blocks participate in a decentralised marketplace by setting prices and trans-ferring data or other digital services in exchange of payments. Figure 1 describes how end users (connectivity consumers) use network applications for their benefit. That requires the consumption of connectivity from the infrastructure (resource system) in the form of traffic in exchange of a compensation that can be economic (pay service). Data and value flows across the different elements of the resource system (network infrastructure). These elements are contributed (deployed and compensated) to the infrastructure according to the capacity needs required (according to the volume of traffic, load and value accumulated). The resource capacity consists on an inventory of devices and an economic balance they can generate under operation as part of the infrastructure. That capacity is the result of the investment of economic resources, with a return that can be measured in terms of social and economic benefits. The investment can come from and return to local (internal) or external participants.

Next, we describe each of the two main groups of key enabling technologies for decen-tralization and disintermediation, blockchain and mesh, and the integration of networking infrastructure, connectivity and other digital services, and the resulting combination of material (network devices), data (connectivity, traffic) and (monetary) value transfers.

3.1   The networking side of it

Structure, participants and governance: In a local network infrastructure we typically find a set of participants that consume connectivity, with devices that act as clients or servers, connected wirelessly to a network access point via cellular or Wi-Fi (a BTS or AP respectively) or wired through Ethernet. Then, we find an intermediary network, that may combine wired or wireless links in a cellular, mesh or static network

topology, connected through layer 2 bridges or layer 3 routers. A dynamic routing protocol collects information to select routes between any two nodes in that network, and ensures reachability and makes routing decisions according to network paths, policies and rules. We focus on wireless mesh networks that use Wi-Fi links, and mesh routing protocols that provide connectivity across any pair of nodes. Finally, we find one or several Internet gateways, that provide internet access, either as layer 3 routers, or layer 7 content proxies like Content Delivery Networks (CDNs) surrogate nodes or web proxies.

Governance: The human network administrators, supported by network management protocols such as the routing, combined with other standard common protocols to allocate identifiers and coordinate the transport of data, provide an effective governance for the network.

Routing, network coordination in a complex world: Routing has to deal with trade-offs between quality and cost, selecting the best routes. However, routing decisions at the network level are related to upper-level decisions. Routing can deal with the internal network but also select default gateways to other networks, and therefore compute the cost to different destinations, not only in terms of performance, but also in economic terms –assuming that each router can define the prices for the forwarding service across their links. In fact, BGP works as a result of agreements with economic implications. In an open environment, security is an issue with multiple facets. Apart from protecting the communications, the result of a cooperative process of forwarding decisions, the network and routing information should be also protected from many types of abuse. The network should be safe and unaffected by faulty, abusive, or adversarial participants. There are ways to cryptographically secure negotiation and establish trusted routing topologies such as Semtor [27], as well as the assessment and detection of anomalous and faulty nodes based on sharing of distributed observations such as kDet [21].

Scalability, capacity, investment and congestion: On a given network configuration, transport protocols deal with network congestion. When congestion spots appear in the access network or a gateway, a reduction of traffic is necessary. This can be achieved by reducing traffic rates or reducing the number of traffic consumers in these spots by trying other paths. However, congestion also signals that traffic has reached the limit of the capacity of the network. Adding more capacity, scaling the network to more participants or further coverage requires changes in the network links and usually an investment in additional capacity that is beyond the network mechanisms and goes into governance decisions, investment and deployment of new capacity.

Productive work as transit, content, services: While the end-to-end principle [32] of the public Internet architecture rebounded around the idea of "dumb" networks and "smart" applications, the Internet has substantially evolved during the last decades of explosive expansion. Nowadays, end-users are typically behind a middlebox (NAT or firewall), for security or scarcity of public IPv4 addresses in the public Internet. The rest of the Internet is reached via routers through Internet carriers. However content and services are less often found directly on remote servers through network transit over the public Internet, but many times these are typically behind private CDNs [17]. Service portals are located adjacent to users, even with delivery spots inside access networks, the CDN surrogates [6].

Scope and locality, towards local traffic and edge delivery: The quality of service or experience (QoS or QoE) for each participant has to do with latency and achievable throughput, that relates to total capacity, usage, and congestion spots. Additionally, the public transit Internet is becoming flatter as content providers get closer

to users. Consequently, network have been pushed to become "smarter" to deal with more complex content and quality expectations. In the 5G 3GPP model [20] controlling low latency and good performance is achieved by not leaving the access network, staying in a layer 2 network while avoiding layer 3 routers. In underserved areas transit and content may be hard to reach. IXPs with low-cost presence of content and transit may be too far and Internet gateways, as transit link or surrogate capacities, may be limited in cost, capacity or reliability. Therefore, there may be a need to balance non-local traffic across multiple separate gateways or connections. This creates an opportunity to share and trade excess capacity across different participants in an access network.

Content delivery: Finally content delivery, through network or content gateways, deals with capacity allocation. If content is delivered by a private CDN through an edge surrogate, achieving this is a private matter between the CDN and the original content or service owner. But if the bottleneck is the access network or a network gateway, load balancing is the solution. Balancing the load across different paths or with another gateway can address the problem.

Diversity of operation and impact models: Networks produce useful connectivity but different networks have different motivations and reasons to build, operate and maintain a network or a group of interconnected networks. That will result in different network structures, topologies, capacities and policies for usage, management and operation.

Inspired by distributed academic networks: In fact, modern computer networks were designed in the academic environment, as well as the interconnection of these to form a decentralized global system. The inter-networking of all these, the Internet, lacks in terms of security and economic protocols, areas where blockchain technology can complement.

3.2   The blockchain side of it

Structure, participants and governance: In a blockchain-based system, we find several key components related to human participants, network devices, procedures that take place, that ultimately result in an ecosystem of services, interactions and immutable data. The participants may need to balance value flows in such ecosystem to ensure sustainability and scalability. That requires to define/attest the identity of human and devices contributed by each, costs and exchange prices, service contracts. While the network and server devices provide connectivity and services and report resource usage, a set of smart contracts can deal with agreements and coordination for service provision and perform settlements to compensate all the participants involved in that provision. These are subject to enforceable governance rules, and result in transactions that report about value exchanges in terms of tokens, resources and services, according to a business or sustainability model. We have found these structures and components in real-world cases such as the guifi.net community network, among other community networks [26].

Digital identity of human participants: Human participants need to have identities, but these identities can be managed by a central authority like a government or a private company like a bank or credit card issuer. This can be decentralised: with self-sovereign identities, an individual has ownership over their personal data with control over how, when, and to whom such data is revealed. Examples are PGP keys, university credentials as used in the Eduroam network, OAuth or OpenID[11].

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[11] https://en.wikipedia.org/wiki/OpenID

Digital identity and ownership of resources: Network resources, such as links, network devices, or servers can be represented as infrastructure tokens: a new device becomes a new title of ownership, that can be represented as the creation of an ERC 721 token[12], a deed associated to each unique device though its serial ID and current owner. Services provided by the infrastructure can result in value transfers (e.g., in fungible token units) to the deeds, that in turn can be forwarded to the current owners of the devices. Infrastructure tokens allow to identify every device, and separate devices from owners. When a device is bought, activated, moved, resold or decommissioned, the corresponding token is updated. This mechanism enables investment models where to buy, deploy and amortise infrastructural components that can be paid back from the payments for usage/service provision.

Governance: A network infrastructure, or a group of them, require governance and regulation. Ideas that fit here are around digital *Decentralised Autonomous Organizations* (DAO)[13] that can automatically oversee, limit, coordinate the overall system, while allowing self-regulation, such as allowing every node or participant to define their own prices or services in that context.

Coordination: In such a network, different procedures ranging from investment, decision making or resource consumption, require structured and credible ways to perform such procedures that involve multiple parties and run across time. Smart contracts can automatically facilitate, verify, or enforce the negotiation or performance of these procedures or contracts, in a traceable and irreversible way. That can result in value transfers in the form of payments of token units. Ideas such as escrows, cheques, become then feasible.

Scalability, capacity, investment, congestion in a collective effort: The result is a collective of investors, providers and consumers. The viability and scalability depends on the ability of the degree of freedom for each device owner to define the prices of the services offered in order to compensate their effort, investment and risk. Each participant should feel motivated to invest and operate in places where there is demand. Each service consumer should have a motivation to consume services, and that is a combination of availability, quality and cost of services. Services require resources, and the excess, lack or fluctuations in demand and offer, or abusive behaviours like hoarding, speculation, result in congestion or instability. A good balance brings high individual and collective social and economic benefits, that enhance social welfare and socio-economic development.

Productive work as transactions: In such decentralised and stipulated environment, transactions can take place, related to resource or service (such as connectivity and content) provision and consumption. Micro-transactions can be considered too, from the smallest possible granularity per byte, packet, flow, link/hop, session such as a VOIP call, or a granularity of a minute, day, month of services. These transactions can be formal and stored, like in blockchain blocks, or micro-transactions or ephemeral side channels across several participants.

Scope and locality of decisions/consensus: When it comes to the scope of the accounting of transactions, we can find local or global, public (open ended to any participant) or private (permissioned) ledgers. A given mesh network may have its own detailed accounting across a few consumers and providers on a informal channel, or more formally in a local ledger, or less detailed or summarised information in a global private or public ledger. In our experimental environment we use a local Ethereum

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[12] http://erc721.org/
[13] https://www.ethereum.org/dao

Proof-of-Authority blockchain combined with a node database and a monitoring repository [18]. Remote access to it, or a gateway to a public blockchain, would allow external participants. This is particularly useful in underserved communities in subsistence economies where external contributions and investment, in economic and material terms, may be required to bootstrap a network.

Diversity of business and impact models: Network infrastructures produce valuable connectivity. Different economic models can relate investment, risk, consumption (how users can buy service), and surpluses (return of investment and benefits). These determine how value is encoded and how this can be tokenised, and therefore minted and exchanged locally and globally.

Inspired by decentralized and solid community networks: In fact, in a large and complex community network like guifi.net we find many of these components: the guifi.net portal allows to create identities for participants that can later used for administrative uses and access to other network services. As part of creating the identity, participants accept the community licence, and therefore the governance model of the "decentralised organization". Participants can then add nodes and links, that are confirmed as detected and validated by the network monitoring system. Network maintainers can associate to these network resources. All CAPEX and OPEX efforts and expenditures can be reported in the economic compensation ledger. Periodically these are settled by the guifi.net Foundation once validated, that can be checked by each participant in its personal section. The network has a reputation system and a conflict resolution system. Therefore, the rather centralised guifi.net portal, combined with the network monitoring system that records resource contribution and consumption, and other supporting services, can be considered the rather centralised equivalent of the DAO in addition to several of the other mechanisms described before.

4   Forms of contribution: service pricing and investment models for network services

Economic sustainability is related to how services are provided and consumed, and what resources are involved. The cost of producing or obtaining connectivity can vary heavily, specifically backhaul Internet connectivity, with differences in the cost of access coverage in rural versus urban areas related to population density and dispersion, as well as differences in the level of income. That affects the amount and form of local investment in the infrastructure, the level of competitive fees with respect to cost and performance, the risk of investment according to the demand, legislation, taxes, regulation, and competition in a given region.

Service pricing: Pricing models relate to payments or compensations in terms of socio-economic value exchanged in return for connectivity or services. High level typical pricing models for services are:

– **Proportional** (Metered): This model provides a pricing directly proportional to usage, per units of cost/service such as bytes, packet, minutes, and therefore more close to the real cost.
– **Constant** (Flat rate for a period): In this model prices are fixed with or without limit. It avoids the risk of unexpected charges, and allows continuous access to the network at a predictable price. Fixed price means that some mechanisms may be needed to limit over-consumption, such as reduction of network service level.

– **Fixed** (Pre-paid per unit of service volume): The volume of service is selected and agreed in advance. Once exhausted, service is blocked. This model is a form of investment, since resources are declared compensated before being used, however it can be used fairly, as that allows planning in the service provision, or unfair, when used to speculate manipulating prices or extracting value for a community.
– **Priority** (Quality discrimination when congestion/load: variable quality): In exchange of lower price, the user accepts degradation of the service in certain periods of excessive usage (congestion). Anyway, that requires a service-level agreement that relates price with expected performance, such as the degree of uncertainty about reduction, duration of low performance periods, etc.
– **Premium** (Quality/capacity differentiation among quality levels): Higher quality and availability of connectivity, implies priority in network access, in exchange of a higher price.
– **Compensation** (Prosumer): participants are both resource contributors and consumers. Payments are the result of compensation or balance between the consumption and contribution of services. This is typical in the IXP, CN or crowdshared models. Community investors fit here as they contribute financial resources in exchange of service provision or the repayment from resource usage.
– **Sponsored** (Free tier): It depends on the sponsor or beneficiary. When the access network is sponsoring some degree of complimentary connectivity (i.e., low rate free traffic to the Internet) the rationale may be to promote the take up of the network, or to allow basic usage (like DNS resolution, system updates, email). The provider will probably be using spare network capacity and therefore the service will have the lowest priority, which will not prevent but complement paid service. When a content provider is sponsoring a free tier, that access will be probably conditioned to visit certain sites the sponsor is willing to pay for. That may be the case when governments or commercial companies promote access and usage to specific content of services of their own interest or benefit. In fact, CDNs are a form of sponsored content and services placed in the proximity of viewers to improve the performance at a reduced access cost.

All these pricing models offer convenient ways for consumers, providers, investors and sponsors (internal or external) to contribute to cover service costs and generate a margin to cater for the recovery of investment, mitigate risks, support growth, and in general produce attractive social and economic benefits for all participants.

Investment and return: In the supply side, there is a big diversity of investment and return (sustainability) models, that can consider environmental (local market and alternative offers); geography, the location and distribution of potential beneficiaries; affordability, as the disposable income for local potential customers or investors; cost of supplies (CAPEX) such as hardware, backhaul, licensing, electricity; cost of operation and maintenance (OPEX); cultural: local demand of voice or data services and content. We have found examples of these models and features in cases such the investment in community shares in B4RN[14], the public matchfunding leases in the Xafogar project[15] or the eXO community investment[16] both in guifi.net. The details are described and discussed in [12, 25].

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[14] Participants are investors, local volunteers and supportive landowners `https://b4rn.org.uk/b4rn-community/`
[15] `https://xafogar.cat/`
[16] `https://exo.cat/contribueix/`

Crowdfunding: Decentralized network infrastructures work as aggregates of many coordinated contributions. The participants can follow diverse goals such as: profit driven, to maximize economic return, from investment; return-of-investment driven, to adjust ROI to target amount or term of expected return; promotion/growth driven, to attract target number/volume of usage; cost driven, to cover costs, sponsored/free, paid by the resource owner or third party such as eduroam, governments, libraries, content providers.

Growth: The growth of a service infrastructure can either be: organic as it grows proportionally with every new participant bringing the additional resources required; demand driven, limited and determined by service demand with investment on expansion reactive to demand; supply driven, limited and determined by the capacity and investment in the infrastructure, with expansion driven by supply limits.

Division of income: Can either be centralised, in the sense that a central entity received all contributions and claims and decides on compensations to all elements or participants; or decentralised, in the sense that contributions flow from consumers are routed across suppliers and each takes a portion proportional to its contribution (cost/price), and there are peer-to-peer compensation/payments across all participants.

5 Discussion

There is an ample diversity of models that, without strong boundaries, combine choices in network structures, service pricing, levels of resource availability, forms of investment, and risk distribution, as illustrated by Figure 2. There are several important distinctions to make when we look at decentralised networks that can be built at scale, therefore crowdfunded, crowdsourced, crowdshared to provide connectivity by aggregation in a given community.
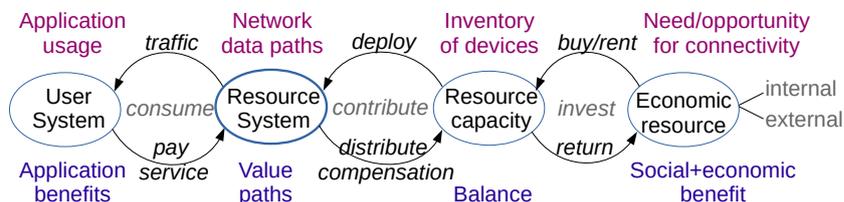

Fig. 2. A few diverse network infrastructure models related to choices in network structure, service pricing, network resource availability, economic investment, and scope of decision risk.

Coupling data and value flows: Traditional network models have shown that despite some business models seem successful in bootstrapping infrastructures, there may be important limitations in scaling up, due to higher coordination and transaction costs, and mainly, about the growing tension from any decoupling between service provision and the economic interactions required to cover the costs. This decoupling results in limitations on the growth of the infrastructure as a result of inefficiencies, lack of profitability or even losses. These barriers can restrict decentralised networks from creating enough socio-economic incentives for investment and service provision, when all relies on voluntary contributions, with risk to fail in generating enough or
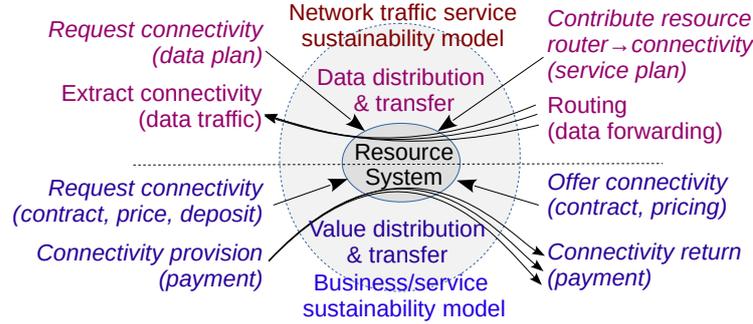
Fig. 3. A network infrastructure as a sustainable resource system from the perspective of data and value flows.

stable benefits such as measurable social impact, income, jobs, that can be reinvested to improve the quality of service or that can accelerate growth.

Commons: open participation in a scalable resource system In fact, crowd-sourced network infrastructures can be described from the perspective of commons or common-pool resources, with the network modelled as a resource system that produces connectivity [26, 12, 25]. Commons should be designed to be sustainable and adaptable as they are critical to sustain the life of a community. For instance, in a classic commons such as an irrigation system, the community supervises water distribution to support agriculture, critical for life and the local economy, and preserve the water source and irrigation system as a common resource for future generations. One additional feature of networking infrastructures is that they are human made (crowdsourced) resource systems, that can be built and extended by the participants to satisfy the needs of an expanding target community, what we call open commons [5]. In a network infrastructure, network monitoring combined with a trusted accounting and economic compensation system seems a requirement to support a commons governance at a non trivial scale, as illustrated in Figure 3 in the context of the overall scheme introduced by Figure 1. The network infrastructure, as a resource system, can be designed and modelled in terms of the feasibility and sustainability of its capacity to handle network traffic (data flow perspective) and therefore handle the distribution and transfer of value (value flow). That design is the result of choices about the technical and socio-economic governance of that resource system. The left side describes the main data and value interactions between a connectivity consumer and the network infrastructure (request connectivity by selecting and activating a contract, and the extraction of connectivity with data traffic in exchange of a payment or contribution). The right side describes the main data and value interactions that involve several components (e.g. access points, routers, Internet gateways) of the infrastructure involved in providing the requested connectivity. All these components contribute resources and provide connectivity services, and perform data forwarding in exchange of a return for that effort.

Consumption and production: connectivity prosumers There is a tension between the individual freedom to join a network by investing in the deployment of network elements, setting target prices or target return of investment goals, and the provision of services, and the collective limits required to preserve the access network

in the long term. These decentralised systems combine pure consumers with many prosumers, brought by the great opportunities for participation in these crowdsourced networks. That requires careful regulation, as part of the governance principles, to determine limits and incentives for participation and investment to ensure a balance.

Economic costs, quality and acceptance: Economic costs are not limited to structural costs. The demand, scarcity or congestion of a resource or service determine its value of exchange, which has an effect on the quality of experience and the number of beneficiaries that can be included. While some applications are quality insensitive (e.g. email, short messages, software updates), other applications rely on capacity (e.g. audio/video content), and some also in short term bursty speed or latency (e.g. audio or video calls or conferencing, online games). Differentiated levels of service to accommodate these usages seem necessary.

Routing data and value: In fact, similarly to the routing function that finds a good network path as the traffic and network conditions vary, the cost sharing compensation function, that can be implemented by a smart contract, can find a good economic balance, as illustrated in Figure 3.

Sustainability and variability: As a network grow, the cost sharing compensations have to deal with the economic matching of collective and individual price expectations and costs [4]. Like in the electricity market, there may be need for a market maker that finds the optimal service prices (e.g. the MBh equivalent to the kWh) or the optimal allocation of connectivity demand and supply that balance the resource system. Such a system can help to accommodate participation, capacity, growth, variability and sustainability.

Policy and regulation: Typical network operators develop top-down which starts from a market analysis, initial capital, capacity and coverage planning, among other ex-ante decisions. Some of this information is required to obtain a license to do business, operate the company, its infrastructure, and provide services. In the "bottom-up" model, a network starts by a single node, and its growth, structure, demand and everything else gets defined and redefined as it evolves. That means the legal procedures for permissions and regulation have to adapt to this "home-made" model [24], and consider, like with traditional commons, the regulation of way leaves, towers and radio spectrum for this activity of socio-economic interest, the collective ownership of a given crowdsourced infrastructure, the taxation of their services and economic activities, the tax incentives for contributions to the infrastructure commons, the consideration of prosumers that can be seen as business agents.

The Universal Service (Access) Funds (USF) is a system of telecommunications subsidies and fees in many countries that collect a tax from telecommunication operators to support universal service, subsidising the connection of the unconnected. One typical use of USF is a Universal Service Obligation (USO) where the most capable telecom provider gets selected to expand coverage in exchange of a subsidy (that tends to be the largest contributor to the USF). Therefore it becomes a program to support the former monopoly operator. Another usage of USF is giving a voucher to residents and businesses to reduce the cost of connectivity in unconnected areas. One example is the "Gigabit Broadband Voucher Scheme" in the UK [13]. This scheme of funding end-users, would allow the funding could be used to develop new local and crowdsourced operators, that contribute better to develop local markets.

In crowdsourced models, with decentralized decision making, with partial or full transparency about facts and decisions, and discretionary or fully detailed information
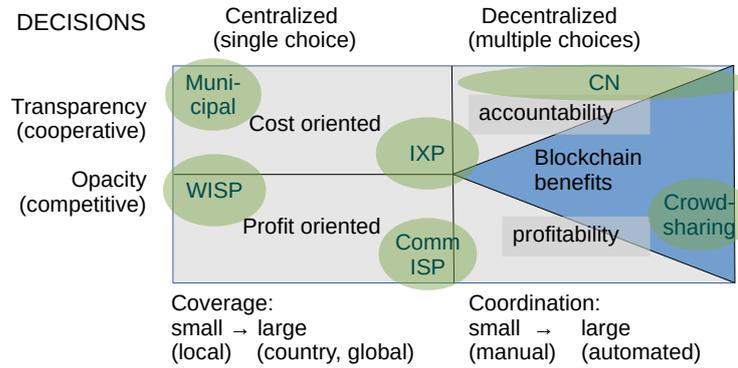
Fig. 4. Organizational models and opportunities for blockchain according to decision making: transparency and decentralization.

(in other words, cooperative or competitive), as illustrated by Figure 4, regulation is key to ensure the correct and optimal operation of the system and prevent anomalies. Blockchain mechanisms can help regulatory agencies and the general public to oversee and ensure the right degree of data and decision transparency, even for very large systems at a reasonable cost. Scalable automated monitoring and supervision systems are needed to ensure the compliance and sustainability of these network infrastructures as they expand, while continuing to comply with existing, local, and global regulatory regimes, similarly as described in [14] for the global energy value chain.

Experiments, lessons and risks: Our experimentation with local blockchains [33] [18], combined with mesh networks in the QMPSU mesh [9] [37] shows the benefits of the integration between service usage, that generates network traffic and Internet access, accounted in each network point, then charged according to a decentralised pricing system, generating cost sharing compensations across the different participants in the access network, or contributing to a reputation system that awards altruistic voluntary contributions or professional activities in a quality oriented reputation system, like the guifi.net network does. That can support the sustainability and profitability of contributing network devices to rapidly expand the coverage and capacity of the network according to demand.

Blockchain benefits from an economics perspective: There are potential benefits from the use of blockchain technology in organisations that take decisions in a decentralised manner, given the decentralised nature of this technology, and its ability to ensure consensus-based append-only state change, among other factors. While some of these decentralised networks are voluntary driven (participants just share their excess Internet connectivity at no cost), others have economic models that rely on contributions by participants to cover shared costs, or rely on external funding or investment (e.g. universal service vouchers). When considering investment and return, growth and decisions to invest may be influenced by the profitability, risk and rate of return of the investment. While a fully cooperative model may rely on full data transparency, a model where some decisions may be discretionary (related to pricing, investment, etc.) needs some degree of information hiding. This is related to Hayek's concept of Catallaxy [15] with the "constitutional ignorance" of rationally bounded [35] participants that cannot

know the exact environmental state (ignorance of all the details behind prices, demand, supply), where participants work for their own interest to maximise utility. In that coordination model, participants communicate and barter through markets, simply as a communication bus, not as a central optimisation component. This is illustrated by Figure 4 that shows the two dimensions of decision making: centralisation (single choice decisions from a centralised agent, versus multiple choices from multiple agents or decentralised decisions) and transparency (cooperative decisions based on full information, or competitive decisions based on partial information, therefore towards opacity). From the Catallaxy perspective, the idea of partial information details, bounded rationality and self-interest in utility maximisation, leads to the concept of profit orientation. As scale grows (both in terms of size like geographic scale or number of participants) this can be addressed by uniformity (single choice in centralised models) or by diversity (multiple choices, including local optimal in decentralised models). However, when combining scale with decentralisation, the guarantees and stipulations provided by blockchain-based mechanisms help to achieve the ideals of accountability and profitability at a reasonable organisational cost through the automation of otherwise too costly operations.

Risks and limitations: However, in the design and implementation we have identified risks related to managing the complexity of payments in local crypto-coins, risks related to coin exchange and fraud, the risk of monetisation of the participation versus altruistic/voluntary contributions, the risk that price fluctuation and traffic fluctuation can create instability in the network and its financial sustainability, which in turn can contribute to the fragility of the infrastructure, and its inclusiveness to keep it open in the long run. For these risks we are exploring mechanisms at different levels to cope with.

6   Related work

There are works that explore aspects of how mesh networks can be combined with blockchain technologies to provide connectivity with an economic model in a decentralised manner.

Several studies provide economic analysis and designs for resource trading. Route Bazaar [8] is a backward-compatible system for flexible Internet connectivity. Inspired by the decentralised construction of trust in cryptocurrencies, Route Bazaar uses a decentralised public ledger and cryptography to provide Autonomous Systems (ASes) with automatic means to form, establish, and verify end-to-end connectivity agreements. Tycoon [19] is a market based distributed resource allocation system based on proportional share that uses auctions for resources, such as computing, storage or network traffic, that uses a centralised bank component based on digitally signed receipts to attest payments, that can be used to claim access and usage of resources later on. Request Network [29] is a decentralised network that allows anyone to request a payment (a Request Invoice) for which the recipient can pay in a secure way. All of the information is stored in a decentralised authentic ledger. Request can be seen as a layer on top of Ethereum which allows requests for payments that satisfy a legal framework.

There are several projects in development that combine mesh networks with blockchain. Althea Mesh [2] provides last-mile connectivity for the Internet access. Althea allows routers to pay each other for bandwidth using cryptocurrency payment channels. Nodes only pay neighbours for forwarding packets. RightMesh [30] is a software-based, ad-hoc mobile mesh networking platform and protocol using blockchain technology and RMESH

tokens. RightMesh integrates into the Ethereum blockchain to provide unique identities for each node in the mesh. Ammbrtech [3] develops solutions that combine networking devices and software tools around a combination of digital identity, local and global blockchain and distributed ledgers, wireless mesh networks, and artificial intelligence to self-adapt the system.

There are several formal or informal schemes where community networks start up by borrowing a few mesh routers and then returning them, returning an equivalent economic value, or better returning equivalent devices bought when the network gathers enough money. This is the case of Coolab [11] or guifi.net among other communities. Several networks have been started from donations, funding programs, or micro-credits that require some level of certification, audit or follow-up. It is also very frequent that when nodes are upgraded the old hardware is donated or sold to another participant with lower requirements. Recent work [31] explores the mapping between the Ostrom's principles [28] for governance of commons, where blockchain technologies can assist by supporting governance processes by automation and traceability to reduce the interaction and transaction costs as communities grow or formalize). Community networks are shown as examples. A smart contract can help to keep track and facilitate these transfers, verification and any economic compensations, particularly when done with at a significant volume.

Finally, this work is based on our experimentation with the QMPSU mesh network, a production network in Barcelona that started in 2011 [9]. The network has reached 100 mesh routers in 2018. It runs a traffic accounting system since 2013, and started to collect usage fees since 2015, but the payments are sent to a traditional bank account. As part of this network, AmmbrTech in collaboration with UPC is running a pilot evaluation of blockchain-based pricing and compensation mechanisms under different pricing schemes [18].

7   Conclusions

We investigate how blockchain technologies and networking technologies can be combined to enable universal connectivity in a decentralised and sustainable manner. Networking infrastructures and services need a balance between the contribution (network capacity) and consumption (network traffic). Economic flows across all participants are required to ensure the right capacity and maintenance of the network (compensating human efforts and economic investment in terms of social and economic return over the long term), and therefore provide satisfactory quality to each participant, and scalability as more participants join.

Our analysis takes into consideration complementary perspectives from the different alternative in terms of organisational and economic models. We first explore the networking aspects of decentralised network infrastructures and services, especially in the context of underserved areas, considering the evolution of Internet connectivity with a mix of transit and content delivery. We then explore how blockchain technologies provide decentralised trusted solutions for the identification of participants and network devices, for the investment and returns from usage fees and cost compensation among the resource providers, and the different aspects of coordination, decision making, and decentralised governance. The result are economic models for decentralised networking infrastructures that aim at balancing contribution and consumption, to be sustainable and scalable.

The tragedy of the commons, the self-interested action by users that result in depleting or spoiling that resource system through their collective action, translates in terms

of connectivity into the tragedy of congestion and failure, where little or no useful connectivity is provided to its users while network resources are over-consumed in terms of queuing, packet drops and re-transmissions. Beyond networking mechanisms for congestion control under existing resources, governance and economic mechanisms are also necessary to ensure the network capacity grows to address the risk of congestion and failure. Economic sustainability is the result of careful consideration of the pricing of network services to be convenient to a wide range of connectivity consumers, affordable and competitive, while promoting investment into the expansion and maintenance of the network. These infrastructures need to generate a positive return and aim at maximising the social value of connectivity for everyone in the target communities.

To the best of our knowledge, our work is the first to analyse the problem space of the intersection between blockchain technologies and networking technologies from the experience of production mesh networks at city scale, with the aim to address the connectivity needs of a global population in the billions. Decentralised solutions, that combine connectivity, data traffic, with flow of value, lower the barrier of entry to the development of connectivity solutions in a crowdsourced manner that promotes participation, and therefore creates social and economic benefits for a wide range of a given population that contribute to sustainable local socio-economic development. Future work will bring quantitative results extracted for the ongoing pilot experiments, and from mature implementations of some of the key components discussed here.

Acknowledgements

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