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Alternative Network Deployments: Taxonomy, Characterization, Technologies, and Architectures

Abstract

This document presents a taxonomy of a set of "Alternative Network Deployments" that emerged in the last decade with the aim of bringing Internet connectivity to people or providing a local communication infrastructure to serve various complementary needs and objectives. They employ architectures and topologies different from those of mainstream networks and rely on alternative governance and business models.

The document also surveys the technologies deployed in these networks, and their differing architectural characteristics, including a set of definitions and shared properties.

The classification considers models such as Community Networks, Wireless Internet Service Providers (WISPs), networks owned by individuals but leased out to network operators who use them as a low-cost medium to reach the underserved population, networks that provide connectivity by sharing wireless resources of the users, and rural utility cooperatives.

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1. Introduction

One of the aims of the Global Access to the Internet for All (GAIA) IRTF Research Group is "to document and share deployment experiences and research results to the wider community through scholarly publications, white papers, Informational and Experimental RFCs, etc." [GAIA]. In line with this objective, this document proposes a classification of "Alternative Network Deployments". This term includes a set of network access models that have emerged in the last decade with the aim of providing Internet connections, following topological, architectural, governance, and business models that differ from the so-called "mainstream" ones, where a company deploys the infrastructure connecting the users, who pay a subscription fee to be connected and make use of it.

Several initiatives throughout the world have built these large-scale networks, using predominantly wireless technologies (including long distance links) due to the reduced cost of using unlicensed spectrum. Wired technologies such as fiber are also used in some of these networks.

The classification considers several types of alternate deployments: Community Networks are self-organized networks wholly owned by the community; networks acting as Wireless Internet Service Providers (WISPs); networks owned by individuals but leased out to network operators who use such networks as a low-cost medium to reach the underserved population; networks that provide connectivity by sharing wireless resources of the users; and finally there are some rural utility cooperatives also connecting their members to the Internet.

The emergence of these networks has been motivated by a variety of factors such as the lack of wired and cellular infrastructures in rural/remote areas [Pietrosemoli]. In some cases, Alternative Networks may provide more localized communication services as well as Internet backhaul support through peering agreements with mainstream network operators. In other cases, they are built as a complement or an alternative to commercial Internet access provided by mainstream network operators.

The present document is intended to provide a broad overview of initiatives, technologies, and approaches employed in these networks, including some real examples. References describing each kind of network are also provided.

1.1. Mainstream Networks

In this document, we will use the term "mainstream networks" to denote those networks sharing these characteristics:

- Regarding scale, they are usually large networks spanning entire regions.
- Top-down control of the network and centralized approach.
- They require a substantial investment in infrastructure.
- Users in mainstream networks do not participate in the network design, deployment, operation, governance, and maintenance.
- Ownership of the network is never vested in the users themselves.

1.2. Alternative Networks

The term "Alternative Network" proposed in this document refers to the networks that do not share the characteristics of "mainstream network deployments". Therefore, they may share some of the following characteristics:

- Relatively small scale (i.e., not spanning entire regions).
- Administration may not follow a centralized approach.
- They may require a reduced investment in infrastructure, which may be shared by the users and commercial and non-commercial entities.
- Users in Alternative Networks may participate in the network design, deployment, operation, and maintenance.
- Ownership of the network is often vested in the users.

2. Terms Used in This Document

Considering the role that the Internet currently plays in everyday life, this document touches on complex social, political, and economic issues. Some of the concepts and terminology used have been the subject of study of various disciplines outside the field of networking and are responsible for long debates whose resolution is out of the scope of this document.

- "Global north" and "global south". Although there is no consensus on the terms to be used when talking about the different development level of countries, we will employ the term "global south" to refer to nations with a relatively lower standard of living. This distinction is normally intended to reflect basic economic country conditions. In common practice, Japan in Asia, Canada and the United States in northern America, Australia and New Zealand in Oceania, and Europe are considered "developed" regions or areas [UN], so we will employ the term "global north" when talking about them.

- The "Digital Divide". The following dimensions are considered to be meaningful when measuring the digital development state of a country: infrastructures (availability and affordability), the Information and Communications Technology (ICT) sector (human capital and technological industry), digital literacy, legal and regulatory framework, and content and services. A lack of digital development in one or more of these dimensions is what has been referred as the "Digital Divide" [Norris]. It should be noted that this "Divide" is not only present between different countries but between zones of the same country, despite its degree of development.

- "Urban" and "rural" zones. There is no single definition of "rural" or "urban", as each country and various international organizations define these terms differently, mainly based on the number of inhabitants, the population density, and the distance between houses [UNStats]. For networking purposes, the primary distinction is likely the average distance between customers, typically measured by population density, as well as the distance to the nearest Internet point-of-presence, i.e., the distance to be covered by "middle mile" or backhaul connectivity. Some regions with low average population density may cluster almost all inhabitants into a small number of relatively dense small towns, for example, while residents may be dispersed more evenly in others.

- Demand. In economics, it describes a consumer's desire and willingness to pay a price for a specific good or service.

- Provision is the act of making an asset available for sale. In this document, we will mainly use it as the act of making a network service available to the inhabitants of a zone.

- Underserved area. Area in which the telecommunication market permanently fails to provide the information and communications services demanded by the population.

o Free, open, and neutral networks. Their principles have been summarized this way [Baig]:

   * You have the freedom to use the network for any purpose as long as you do not harm the operation of the network itself, the rights of other users, or the principles of neutrality that allow contents and services to flow without deliberate interference.

   * You have the right to understand the network, to know its components, and to spread knowledge of its mechanisms and principles.

   * You have the right to offer services and content to the network on your own terms.

   * You have the right to join the network, and the responsibility to extend this set of rights to anyone according to these same terms.

3. Scenarios Where Alternative Networks Are Deployed

Different studies have reported that as much as 60% of the people on the planet do not have Internet connectivity [Sprague] [InternetStats]. In addition, those unconnected are unevenly distributed: only 31% of the population in "global south" countries had access in 2014, against 80% in "global north" countries [WorldBank2016]. This is one of the reasons behind the inclusion of the objective to "significantly increase access to information and communications technology and strive to provide universal and affordable access to the Internet in least developed countries by 2020," as one of the targets in the Sustainable Development Goals (SDGs) [SDG], considered as a part of "Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation."

For the purpose of this document, a distinction between "global north" and "global south" zones is made, highlighting the factors related to ICT, which can be quantified in terms of:

o The availability of both national and international bandwidth, as well as equipment.

o The difficulty in paying for the services and the devices required to access the ICTs.

o The instability and/or lack of power supply.

- The scarcity of qualified staff.

- The existence of a policy and regulatory framework that hinders the development of these models in favor of state monopolies or incumbents.

In this context, the World Summit of the Information Society [WSIS] aimed at achieving "a people-centred, inclusive and development-oriented Information Society, where everyone can create, access, utilize and share information and knowledge. Therefore, enabling individuals, communities and people to achieve their full potential in promoting their sustainable development and improving their quality of life". It also called upon "governments, private sector, civil society and international organizations" to actively engage to work towards the bridging of the digital divide.

Some Alternative Networks have been deployed in underserved areas, where citizens may be compelled to take a more active part in the design and implementation of ICT solutions. However, Alternative Networks (e.g., [Baig]) are also present in some "global north" countries, being built as an alternative to commercial ones managed by mainstream network operators.

The consolidation of a number of mature Alternative Networks (e.g., Community Networks) sets a precedent for civil society members to become more active in the search for alternatives to provide themselves with affordable access. Furthermore, Alternative Networks could contribute to bridge the digital divide by increasing human capital and promoting the creation of localized content and services.

3.1. Urban vs. Rural Areas

The differences presented in the previous section are not only present between countries, but within them too. This is especially the case for rural inhabitants, who represent approximately 55% of the world's population [IFAD2011], with 78% of them in "global south" countries [ITU2011]. According to the World Bank, adoption gaps "between rural and urban populations are falling for mobile phones but increasing for the internet" [WorldBank2016].

Although it is impossible to generalize among them, there exist some common features in rural areas that have prevented incumbent operators from providing access and that, at the same time, challenge the deployment of alternative infrastructures [Brewer] [Nungu] [Simo_c]. For example, a high network latency was reported in [Johnson_b], which could be in the order of seconds during some hours.

These challenges include:

- o Low per capita income, as the local economy is mainly based on subsistence agriculture, farming, and fishing.

- o Scarcity or absence of basic infrastructures, such as electricity, water, and access roads.

- o Low population density and distance (spatial or effective) between population clusters.

- o Underdeveloped social services, such as healthcare and education.

- o Lack of adequately educated and trained technicians, and high potential for those (few) trained to leave the community incentivized by better opportunities, higher salaries, or the possibility of starting their own companies [McMahon].

- o High cost of Internet access [Mathee].

- o Harsh environments leading to failure in electronic communication devices [Johnson_a], which reduces the reliability of the network.

Some of these factors challenge the stability of Alternative Networks and the services they provide: scarcity of spectrum, scale, and heterogeneity of devices. However, the proliferation of Alternative Networks [Baig] together with the raising of low-cost, low-consumption, low-complexity off-the-shelf wireless devices have allowed and simplified the deployment and maintenance of alternative infrastructures in rural areas.

3.2. Topology Patterns Followed by Alternative Networks

Alternative Networks, considered self-managed and self-sustained, follow different topology patterns [Vega_a]. Generally, these networks grow spontaneously and organically, that is, the network grows without specific planning and deployment strategy and the routing core of the network tends to fit a power law distribution. Moreover, these networks are composed of a high number of heterogeneous devices with the common objective of freely connecting and increasing the network coverage and the reliability. Although these characteristics increase the entropy (e.g., by increasing the number of routing protocols), they have resulted in an inexpensive solution to effectively increase the network size. One such example is Guifi.net [Vega_a], which has had an exponential growth rate in the number of operating nodes during the last decade.

Regularly, rural areas in these networks are connected through long-distance links and/or wireless mesh networks, which in turn convey the Internet connection to relevant organizations or institutions. In contrast, in urban areas, users tend to share and require mobile access. Since these areas are also likely to be covered by commercial ISPs, the provision of wireless access by virtual operators like [Fon] may constitute a way to extend the user capacity to the network. Other proposals like "Virtual Public Networks" [Sathiaseelan_a] can also extend the service.

4. Classification Criteria

The classification of Alternative Network Deployments, presented in this document, is based on the following criteria:

4.1. Entity behind the Network

The entity (or entities) or individuals behind an Alternative Network can be:

- A community of users.
- A public stakeholder.
- A private company.
- Supporters of a crowdshared approach.
- A community that already owns the infrastructure and shares it with an operator, who, in turn, may also use it for backhauling purposes.
- A research or academic entity.

The above actors may play different roles in the design, financing, deployment, governance, and promotion of an Alternative Network. For example, each of the members of a Community Network maintains the ownership over the equipment they have contributed, whereas in others there is a single entity, e.g., a private company who owns the equipment, or at least a part of it.

4.2. Purpose

Alternative Networks can be classified according to their purpose and the benefits they bring compared to mainstream solutions, regarding economic, technological, social, or political objectives. These benefits could be enjoyed mostly by the actors involved (e.g., lowering costs or gaining technical expertise) or by the local community (e.g., Internet access in underserved areas) or by the society as a whole (e.g., network neutrality).

The benefits provided by Alternative Networks include, but are not limited to:

- Extending coverage to underserved areas (users and communities).

- Providing affordable Internet access for all.

- Reducing initial capital expenditures (for the network and the end user, or both).

- Providing additional sources of capital (beyond the traditional carrier-based financing).

- Reducing ongoing operational costs (such as backhaul or network administration).

- Leveraging expertise and having a place for experimentation and teaching.

- Reducing hurdles to adoption (e.g., digital literacy, literacy in general, and relevance).

- Providing an alternative service in case of natural disasters and other extreme situations.

- Community building, social cohesion, and quality of life improvement.

- Experimentation with alternative governance and ownership models for treating network infrastructures as a commons.

- Raising awareness of political debates around issues like network neutrality, knowledge sharing, access to resources, and more.

Note that the different purposes of Alternative Networks can be more or less explicitly stated and they could also evolve over time based on the internal dynamics and external events. For example, the Red Hook WIFI network in Brooklyn [Redhook] started as a Community Network focusing more on local applications and community building [TidePools], but it became widely known when it played a key role as an alternative service available during the Sandy storm [Tech] [NYTimes].

Moreover, especially for those networks with more open and horizontal governance models, the underlying motivations of those involved may be very diverse, ranging from altruistic ones related to the desire of free sharing of Internet connectivity and various forms of activism to personal benefits from the experience and expertise through the active participation in the deployment and management of a real and operational network.

4.3. Governance and Sustainability Model

Different governance models are present in Alternative Networks. They may range from some open and horizontal models, with an active participation of the users (e.g., Community Networks) to a more centralized model, where a single authority (e.g., a company or a public stakeholder) plans and manages the network, even if it is (total or partially) owned by a community.

Regarding sustainability, some networks grow "organically" as a result of the new users who join and extend the network, contributing their own hardware. In some other cases, the existence of previous infrastructure (owned by the community or the users) may lower the capital expenditures of an operator, who can therefore provide the service with better economic conditions.

4.4. Technologies Employed

- Standard Wi-Fi. Many Alternative Networks are based on the standard IEEE 802.11 [IEEE.802.11] using the Distributed Coordination Function.

- Wi-Fi-based Long Distance (WiLD) networks. These can work with either Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) or an alternative Time Division Multiple Access (TDMA) Media Access Control (MAC) [Simo_b].

- TDMA. It can be combined with a Wi-Fi protocol, in a non-standard way [airMAX]. This configuration allows each client to send and receive data using pre-designated timeslots.

- 802.16-compliant (Worldwide Interoperability for Microwave Access (WiMax)) [IEEE.802.16] systems over non-licensed bands.

- Dynamic Spectrum Solutions (e.g., based on the use of TV White Spaces). A set of television frequencies that can be utilized by secondary users in locations where they are unused, e.g., IEEE 802.11af [IEEE.802.11AF] or 802.22 [IEEE.802.22].

- Satellite solutions can also be employed to give coverage to wide areas, as proposed in the RIFE project (https://rife-project.eu/).

- Low-cost optical fiber systems are also used to connect households in different places.

4.5. Typical Scenarios

The scenarios where Alternative Networks are usually deployed can be classified as:

- Urban/rural areas.

- "Global north" / "global south" countries.

5. Classification of Alternative Networks

This section classifies Alternative Networks according to the criteria explained previously. Each of them has different incentive structures, maybe common technological challenges, but most importantly interesting usage challenges that feed into the incentives as well as the technological challenges.

At the beginning of each subsection, a table is presented including a classification of each network according to the criteria listed in the "Classification Criteria" subsection. Real examples of each kind of Alternative Network are cited.

5.1. Community Networks

Entity behind the network	community
Purpose	all the goals listed in Section 4.2 may be present
Governance and sustainability model	participatory administration model: non-centralized and open building and maintenance; users may contribute their own hardware
Technologies employed	Wi-Fi [IEEE.802.11] (standard and non-standard versions) and optical fiber
Typical scenarios	urban and rural

Table 1: Characteristics Summary for Community Networks

Community Networks are non-centralized, self-managed networks sharing these characteristics:

o They start and grow organically, and they are open to participation from everyone, sharing an open participation agreement. Community members directly contribute active (not just passive) network infrastructure. The network grows as new hosts and links are added.

o Knowledge about building and maintaining the network and ownership of the network itself is non-centralized and open. Different degrees of centralization can be found in Community Networks. In some of them, a shared platform (e.g., a website) may exist where minimum coordination is performed. Community members with the right permissions have an obvious and direct form of organizational control over the overall organization of the network (e.g., IP addresses, routing, etc.) in their community (not just their own participation in the network).

o The network can serve as a backhaul for providing a whole range of services and applications, from completely free to even commercial services.

Hardware and software used in Community Networks can be very diverse and customized, even inside one network. A Community Network can have both wired and wireless links. Multiple routing protocols or network topology management systems may coexist in the network.

These networks grow organically, since they are formed by the aggregation of nodes belonging to different users. A minimal governance infrastructure is required in order to coordinate IP addressing, routing, etc. Several examples of Community Networks are described in [Braem]. A technological analysis of a Community Network is presented in [Vega_b], which focuses on technological network diversity, topology characteristics, the evolution of the network over time, robustness and reliability, and networking service availability.

These networks follow a participatory administration model, which has been shown to be effective in connecting geographically dispersed people, thus enhancing and extending digital Internet rights.

Users adding new infrastructure (i.e., extensibility) can be used to formulate another definition: A Community Network is a network in which any participant in the system may add link segments to the network in such a way that the new segments can support multiple nodes and adopt the same overall characteristics as those of the joined network, including the capacity to further extend the network. Once these link segments are joined to the network, there is no longer a meaningful distinction between the previous and the new extent of the network. The term "participant" refers to an individual, who may become the user, provider, and manager of the network at the same time.

In Community Networks, profit can only be made by offering services and not simply by supplying the infrastructure, because the infrastructure is neutral, free, and open (mainstream Internet Service Providers base their business on the control of the infrastructure). In Community Networks, everybody usually keeps the ownership of what he/she has contributed or leaves the stewardship of the equipment to the network as a whole (the commons), even loosing track of the ownership of a particular equipment itself, in favor of the community.

The majority of Community Networks comply with the definition of Free Network, included in Section 2.

5.2. Wireless Internet Service Providers (WISPs)

Entity behind the network	company
Purpose	to serve underserved areas; to reduce capital expenditures in Internet access; and to provide additional sources of capital
Governance and sustainability model	operated by a company that provides the equipment; centralized administration
Technologies employed	wireless, e.g., [IEEE.802.11] and [IEEE.802.16] and unlicensed frequencies
Typical scenarios	rural (urban deployments also exist)

Table 2: Characteristics Summary for WISPs

WISPs are commercially operated wireless Internet networks that provide Internet and/or Voice over Internet (VoIP) services. They are most common in areas not covered by mainstream telecommunications companies or ISPs. WISPs mostly use wireless point-to-multipoint links using unlicensed spectrum but often must resort to licensed frequencies. Use of licensed frequencies is common in regions where unlicensed spectrum is either perceived to be crowded or too unreliable to offer commercial services, or where unlicensed spectrum faces regulatory barriers impeding its use.

Most WISPs are operated by local companies responding to a perceived market gap. There is a small but growing number of WISPs, such as [Airjaldi] in India, that have expanded from local service into multiple locations.

Since 2006, the deployment of cloud-managed WISPs has been possible with hardware from companies such as [Meraki] and later [OpenMesh] and others. Until recently, however, most of these services have been aimed at "global north" markets. In 2014, a cloud-managed WISP service aimed at "global south" markets was launched [Everylayer].

5.3. Shared Infrastructure Model

Entity behind the network	shared: companies and users
Purpose	to eliminate a capital expenditures barrier (to operators); lower the operating expenses (supported by the community); and extend coverage to underserved areas
Governance and sustainability model	the community rents the existing infrastructure to an operator
Technologies employed	wireless in non-licensed bands, mobile femtocells, WiLD networks [WiLD], and/or low-cost fiber
Typical scenarios	rural areas, and more particularly rural areas in "global south" regions

Table 3: Characteristics Summary for Shared Infrastructure

In mainstream networks, the operator usually owns the telecommunications infrastructure required for the service or sometimes rents infrastructure to/from other companies. The problem arises in large areas with low population density, in which neither the operator nor the other companies have deployed infrastructure and such deployments are not likely to happen due to the low potential return on investment.

When users already own deployed infrastructure, either individually or as a community, sharing that infrastructure with an operator can benefit both parties and is a solution that has been deployed in some areas. For the operator, this provides a significant reduction in the initial investment needed to provide services in small rural localities because capital expenditure is only associated with the access network. Renting capacity in the users' network for backhauling only requires an increment in the operating expenditure. This approach also benefits the users in two ways: they obtain improved access to telecommunications services that would not be accessible otherwise, and they can derive some income from the operator that helps to offset the network's operating costs, particularly for network maintenance.

One clear example of the potential of the "shared infrastructure model" nowadays is the deployment of 3G services in rural areas in which there is a broadband rural Community Network. Since the inception of femtocells (small, low-power cellular base stations), there are complete technical solutions for low-cost 3G coverage using the Internet as a backhaul. If a user or community of users has an IP network connected to the Internet with some excess capacity, placing a femtocell in the user premises benefits both the user and the operator, as the user obtains better coverage and the operator does not have to support the cost of the backhaul infrastructure. Although this paradigm was conceived for improved indoor coverage, the solution is feasible for 3G coverage in underserved rural areas with low population density (i.e., villages), where the number of simultaneous users and the servicing area are small enough to use low-cost femtocells. Also, the amount of traffic produced by these cells can be easily transported by most community broadband rural networks.

Some real examples can be referenced in the TUCAN3G project, which deployed demonstrator networks in two regions in the Amazon forest in Peru [Simo_d]. In these networks [Simo_a], the operator and several rural communities cooperated to provide services through rural networks built up with WiLD links [WiLD]. In these cases, the networks belonged to the public health authorities and were deployed with funds that came from international cooperation for telemedicine purposes. Publications that justify the feasibility of this approach can also be found on that website.

5.4. Crowdshared Approaches Led by the Users and Third-Party Stakeholders

Entity behind the network	community, public stakeholders, private companies, and supporters of a crowdshared approach
Purpose	sharing connectivity and resources
Governance and sustainability model	users share their capacity, coordinated by a Virtual Network Operator (VNO); different models may exist, depending on the nature of the VNO
Technologies employed	Wi-Fi [IEEE.802.11]
Typical scenarios	urban and rural

Table 4: Characteristics Summary for Crowdshared Approaches

These networks can be defined as a set of nodes whose owners share common interests (e.g., sharing connectivity; resources; and peripherals) regardless of their physical location. They conform to the following approach: the home router creates two wireless networks -- one of them is normally used by the owner, and the other one is public. A small fraction of the bandwidth is allocated to the public network to be employed by any user of the service in the immediate area. Some examples are described in [PAWS] and [Sathiaseelan_c]. Other examples are found in the networks created and managed by city councils (e.g., [Heer]). The "openwireless movement" (https://openwireless.org/) also promotes the sharing of private wireless networks.

Some companies [Fon] also promote the use of Wi-Fi routers with dual access: a Wi-Fi network for the user and a shared one. Adequate Authentication, Authorization, and Accounting (AAA) policies are implemented, so people can join the network in different ways: they can buy a router, so they can share their connection and in turn, they get access to all the routers associated with the community. Some users can even get some revenue every time another user connects to their Wi-Fi Access Point. Users that are not part of the community can buy passes in order to use the network. Some mainstream telecommunications operators collaborate with these communities by including the functionality required to create the two access networks in their routers. Some of these efforts are surveyed in [Shi].

The elements involved in a crowdshared network are summarized below:

o Interest: A parameter capable of providing a measure (cost) of the attractiveness of a node in a specific location, at a specific instance in time.

o Resources: A physical or virtual element of a global system. For instance, bandwidth; energy; data; and devices.

o The owner: End users who sign up for the service and share their network capacity. As a counterpart, they can access another owner's home network capacity for free. The owner can be an end user or an entity (e.g., operator; virtual mobile network operator; or municipality) that is to be made responsible for any actions concerning his/her device.

o The user: A legal entity or an individual using or requesting a publicly available electronic communications service for private or business purposes, without necessarily having subscribed to such service.

o The VNO: An entity that acts in some aspects as a network coordinator. It may provide services such as initial authentication or registration and, eventually, trust relationship storage. A VNO is not an ISP given that it does not provide Internet access (e.g., infrastructure or naming). A VNO is not an Application Service Provider (ASP) either since it does not provide user services. VNOs may also be stakeholders with socio-environmental objectives. They can be local governments, grassroots user communities, charities, or even content operators, smart grid operators, etc. They are the ones who actually run the service.

o Network operators: They have a financial incentive to lease out unused capacity [Sathiaseelan_b] at a lower cost to the VNOs.

VNOs pay the sharers and the network operators, thus creating an incentive structure for all the actors: the end users get money for sharing their network, and the network operators are paid by the VNOs, who in turn accomplish their socio-environmental role.

5.5. Rural Utility Cooperatives

Entity behind the network	rural utility cooperative
Purpose	to serve underserved areas and to reduce capital expenditures in Internet access
Governance and sustainability model	the cooperative partners with an ISP who manages the network
Technologies employed	wired (fiber) and wireless
Typical scenarios	rural

Table 5: Characteristics Summary for Rural Utility Cooperatives

A utility cooperative is a type of cooperative that delivers a public utility to its members. For example, in the United States, rural electric cooperatives have provided electric service starting in the 1930s, especially in areas where investor-owned utility would not provide service, believing there would be insufficient revenue to justify the capital expenditures required. Similarly, in many regions with low population density, traditional Internet Service Providers such as telephone companies or cable TV companies are either not providing service at all or only offering low-speed DSL service. Some rural electric cooperatives started installing fiber optic lines to run their smart grid applications, but they found they could provide fiber-based broadband to their members at little additional cost [Cash]. In some of these cases, rural electric cooperatives have partnered with local ISPs to provide Internet connection to their members [Carlson]. More information about these utilities and their management can be found in [NewMexico] and [Mitchell].

5.6. Testbeds for Research Purposes

Entity behind the network	research/academic entity
Purpose	research
Governance and sustainability model	the management is initially coordinated by the research entity, but it may end up in a different model
Technologies employed	wired and wireless
Typical scenarios	urban and rural

Table 6: Characteristics Summary for Testbeds

In some cases, the initiative to start the network is not from the community but from a research entity (e.g., a university), with the aim of using it for research purposes [Samanta] [Bernardi].

The administration of these networks may start being centralized in most cases (administered by the academic entity) and may end up in a non-centralized model in which other local stakeholders assume part of the network administration (for example, see [Rey]).

6. Technologies Employed

6.1. Wired

In many ("global north" or "global south") countries, it may happen that national service providers decline to provide connectivity to tiny and isolated villages. So in some cases, the villagers have created their own optical fiber networks. This is the case in Lowenstedt, Germany [Lowenstedt] or in some parts of Guifi.net [Cerda-Alabern].

6.2. Wireless

The vast majority of Alternative Network Deployments are based on different wireless technologies [WNDW]. Below we summarize the options and trends when using these features in Alternative Networks.

6.2.1. Media Access Control (MAC) Protocols for Wireless Links

Different protocols for MAC, which also include physical layer (PHY) recommendations, are widely used in Alternative Network Deployments. Wireless standards ensure interoperability and usability to those who design, deploy, and manage wireless networks. In addition, they then ensure the low cost of equipment due to economies of scale and mass production.

The standards used in the vast majority of Alternative Networks come from the IEEE Standard Association's IEEE 802 Working Group. Standards developed by other international entities can also be used, such as, e.g., the European Telecommunications Standards Institute (ETSI).

6.2.1.1. 802.11 (Wi-Fi)

The standard we are most interested in is 802.11 a/b/g/n/ac, as it defines the protocol for Wireless LAN. It is also known as "Wi-Fi". The original release (a/b) was issued in 1999 and allowed for rates up to 54 Mbit/s. The latest release (802.11ac) approved in 2013 reaches up to 866.7 Mbit/s. In 2012, the IEEE issued an 802.11 standard that consolidated all the previous amendments [IEEE.802.11]. The document is freely downloadable from the IEEE Standards Association [IEEE].

The MAC protocol in 802.11 is called CSMA/CA and was designed for short distances; the transmitter expects the reception of an acknowledgment for each transmitted unicast packet and if a certain waiting time is exceeded, the packet is retransmitted. This behavior makes necessary the adaptation of several MAC parameters when 802.11 is used in long links [Simo_b]. Even with this adaptation, distance has a significant negative impact on performance. For this reason, many vendors implement alternative medium access techniques that are offered alongside the standard CSMA/CA in their outdoor 802.11 products. These alternative proprietary MAC protocols usually employ some type of TDMA. Low-cost equipment using these techniques can offer high throughput at distances above 100 kilometers.

Different specifications of 802.11 operate in different frequency bands. 802.11b/g/n operates in 2.4 GHz, but 802.11a/n/ac operates in 5 GHz. This fact is used in some Community Networks in order to separate ordinary and "backbone" nodes:

- o Typical routers running mesh firmware in homes, offices, and public spaces operate at 2.4 GHz.

- o Special routers running mesh firmware as well but broadcasting and receiving on the 5 GHz band are used in point-to-point connections only. They are helpful to create a "backbone" on the network that can both connect neighborhoods to one another when reasonable connections with 2.4 GHz nodes are not possible, and they ensure that users of 2.4 GHz nodes are within a few hops to strong and stable connections to the rest of the network.

6.2.1.2. Mobile Technologies

Global System for Mobile Communications (GSM), from ETSI, has also been used in Alternative Networks as a Layer 2 option, as explained in [Mexican], [Village], and [Heimerl]. Open source GSM code projects such as OpenBTS (http://openbts.org) or OpenBSC (http://openbsc.osmocom.org/trac/) have created an ecosystem with the participation of several companies such as, e.g., [Rangenetworks], [Endaga], and [YateBTS]. This enables deployments of voice, SMS, and Internet services over Alternative Networks with an IP-based backhaul.

Internet navigation is usually restricted to relatively low bit rates (see, e.g., [Osmocom]). However, leveraging on the evolution of Third Generation Partnership Project (3GPP) standards, a trend can be observed towards the integration of 4G [Spectrum] [YateBTS] or 5G [Openair] functionalities, with significant increase of achievable bit rates.

Depending on factors such as the allocated frequency band, the adoption of licensed spectrum can have advantages over the eventually higher frequencies used for Wi-Fi, in terms of signal propagation and, consequently, coverage. Other factors favorable to 3GPP technologies, especially GSM, are the low cost and energy consumption of handsets, which facilitate its use by low-income communities.

6.2.1.3. Dynamic Spectrum

Some Alternative Networks make use of TV White Spaces [Lysko] -- a set of UHF and VHF television frequencies that can be utilized by secondary users in locations where they are unused by licensed primary users such as television broadcasters. Equipment that makes use of TV White Spaces is required to detect the presence of existing unused TV channels by means of a spectrum database and/or spectrum sensing in order to ensure that no harmful interference is caused to primary users. In order to smartly allocate interference-free channels to the devices, cognitive radios are used that are able to modify their frequency, power, and modulation techniques to meet the strict operating conditions required for secondary users.

The use of the term "White Spaces" is often used to describe "TV White Spaces" as the VHF and UHF television frequencies were the first to be exploited on a secondary use basis. There are two dominant standards for TV White Space communication: (i) the 802.11af standard [IEEE.802.11AF] -- an adaptation of the 802.11 standard for TV White Space bands -- and (ii) the IEEE 802.22 standard [IEEE.802.22] for long-range rural communication.

6.2.1.3.1. 802.11af

802.11af [IEEE.802.11AF] is a modified version of the 802.11 standard operating in TV White Space bands using cognitive radios to avoid interference with primary users. The standard is often referred to as "White-Fi" or "Super Wi-Fi" and was approved in February 2014. 802.11af contains much of the advances of all the 802.11 standards including recent advances in 802.11ac such as up to four bonded channels, four spatial streams, and very high-rate 256 QAM (Quadrature Amplitude Modulation) but with improved in-building penetration and outdoor coverage. The maximum data rate achievable is 426.7 Mbit/s for countries with 6/7 MHz channels and 568.9 Mbit/s for countries with 8 MHz channels. Coverage is typically limited to 1 km although longer range at lower throughput and using high gain antennas will be possible.

Devices are designated as enabling stations (Access Points) or dependent stations (clients). Enabling stations are authorized to control the operation of a dependent station and securely access a geolocation database. Once the enabling station has received a list of available White Space channels, it can announce a chosen channel to the dependent stations for them to communicate with the enabling station. 802.11af also makes use of a registered location server -- a local database that organizes the geographic location and operating parameters of all enabling stations.

6.2.1.3.2. 802.22

802.22 [IEEE.802.22] is a standard developed specifically for long-range rural communications in TV White Space frequencies and was first approved in July 2011. The standard is similar to the 802.16 (WiMax) [IEEE.802.16] standard with an added cognitive radio ability. The maximum throughput of 802.22 is 22.6 Mbit/s for a single 8 MHz channel using 64-QAM modulation. The achievable range using the default MAC scheme is 30 km; however, 100 km is possible with special scheduling techniques. The MAC of 802.22 is specifically customized for long distances -- for example, slots in a frame destined for more distant Consumer Premises Equipment (CPE) are sent before slots destined for nearby CPEs.

Base stations are required to have a Global Positioning System (GPS) and a connection to the Internet in order to query a geolocation spectrum database. Once the base station receives the allowed TV channels, it communicates a preferred operating TV White Space channel with the CPE devices. The standard also includes a coexistence mechanism that uses beacons to make other 802.22 base stations aware of the presence of a base station that is not part of the same network.

7. Upper Layers

7.1. Layer 3

7.1.1. IP Addressing

Most Community Networks use private IPv4 address ranges, as defined by [RFC1918]. The motivation for this was the lower cost and the simplified IP allocation because of the large available address ranges.

Most known Alternative Networks started in or around the year 2000. IPv6 was fully specified by then, but almost all Alternative Networks still use IPv4. A survey [Avonts] indicated that IPv6 rollout presented a challenge to Community Networks. However, some of them have already adopted it, such as ninux.org.

7.1.2. Routing Protocols

As stated in previous sections, Alternative Networks are composed of possibly different Layer 2 devices, resulting in a mesh of nodes. A connection between different nodes is not guaranteed, and the link stability can vary strongly over time. To tackle this, some Alternative Networks use mesh routing protocols for Mobile Ad Hoc Networks (MANETs), while other ones use more traditional routing protocols. Some networks operate multiple routing protocols in parallel. For example, they may use a mesh protocol inside different islands and rely on traditional routing protocols to connect these islands.

7.1.2.1. Traditional Routing Protocols

The Border Gateway Protocol (BGP), as defined by [RFC4271], is used by a number of Community Networks because of its well-studied behavior and scalability.

For similar reasons, smaller networks opt to run the Open Shortest Path First (OSPF) protocol, as defined by [RFC2328].

7.1.2.2. Mesh Routing Protocols

A large number of Alternative Networks use customized versions of the Optimized Link State Routing (OLSR) Protocol [RFC3626]. The open source project [OLSR] has extended the protocol with the Expected Transmission Count (ETX) metric [Couto] and other features for its use in Alternative Networks, especially wireless ones. A new version of the protocol, named OLSRv2 [RFC7181], is becoming used in some Community Networks [Barz].

Better Approach To Mobile Ad Hoc Networking (B.A.T.M.A.N.) Advanced [Seither] is a Layer 2 routing protocol, which creates a bridged network and allows seamless roaming of clients between wireless nodes.

Some networks also run the BatMan-eXperimental Version 6 (BMX6) protocol [Neumann_a], which is based on IPv6 and tries to exploit the social structure of Alternative Networks.

Babel [RFC6126] is a Layer 3 loop-avoiding distance-vector routing protocol that is robust and efficient both in wired and wireless mesh networks.

In [Neumann_b], a study of three proactive mesh routing protocols (BMX6, OLSR, and Babel) is presented, in terms of scalability, performance, and stability.

7.2. Transport Layer

7.2.1. Traffic Management When Sharing Network Resources

When network resources are shared (as, e.g., in the networks explained in Section 5.4), special care has to be taken with the management of the traffic at upper layers. From a crowdshared perspective, and considering just regular TCP connections during the critical sharing time, the Access Point offering the service is likely to be the bottleneck of the connection.

This is the main concern of sharers, having several implications. In some cases, an adequate Active Queue Management (AQM) mechanism that implements a Less-than-Best-Effort (LBE) [RFC6297] policy for the user is used to protect the sharer. Achieving LBE behavior requires the appropriate tuning of well-known mechanisms such as Explicit Congestion Notification (ECN) [RFC3168], Random Early Detection (RED) [RFC7567], or other more recent AQM mechanisms that aid low latency such as Controlled Delay (CoDel) [CoDel] and Proportional Integral controller Enhanced (PIE) [PIE] design.

7.3. Services Provided

This section provides an overview of the services provided by the network. Many Alternative Networks can be considered Autonomous Systems, being (or aspiring to be) a part of the Internet.

The services provided can include, but are not limited to:

- Web browsing.

- Email.

- Remote desktop (e.g., using my home computer and my Internet connection when I am away).

- FTP file sharing (e.g., distribution of software and media).

- VoIP (e.g., with SIP).

- Peer-to-Peer (P2P) file sharing.

- Public video cameras.

- DNS.

- Online game servers.

- Jabber instant messaging.

- Weather stations.

- Network monitoring.

- Videoconferencing/streaming.

- Radio streaming.

- Message/bulletin board.

- Local cloud storage services.

Due to bandwidth limitations, some services (file sharing, VoIP, etc.) may not be allowed in some Alternative Networks. In some of these cases, a number of federated proxies provide web-browsing service for the users.

Some specialized services have been specifically developed for Alternative Networks:

- o Inter-network peering/VPNs (e.g., https://wiki.freifunk.net/IC-VPN).
- o Community-oriented portals (e.g., http://tidepools.co/).
- o Network monitoring/deployment/maintenance platforms.
- o VoIP sharing between networks, allowing cheap calls between countries.
- o Sensor networks and citizen science built by adding sensors to devices.
- o Community radio/TV stations.

Other services (e.g., local wikis as used in community portals; see https://localwiki.org) can also provide useful information when supplied through an Alternative Network, although they were not specifically created for them.

7.3.1. Use of VPNs

Some "micro-ISPs" may use the network as a backhaul for providing Internet access, setting up VPNs from the client to a machine with Internet access.

Many Community Networks also use VPNs to connect multiple disjoint parts of their networks together. In some others, every node establishes a VPN tunnel as well.

7.3.2. Other Facilities

Other facilities, such as NTP or Internet Relay Chat (IRC) servers may also be present in Alternative Networks.

7.4. Security Considerations

No security issues have been identified for this document.

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