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Accepted from Open Call

Alternative Networks: Toward a Global Access to the Internet for All

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It is often said that the Internet is ubiquitous in our daily lives, but this holds true only for those who can easily access it. In fact, billions of people are still digitally-disconnected, as bringing connectivity to certain zones does not make a good business case. The only solution for these unsatisfied potential users is to directly undertake the building of the infrastructure required to obtaining access to the Internet, typically forming groups in order to share the corresponding cost.

Abstract

It is often said that the Internet is ubiquitous in our daily lives, but this holds true only for those who can easily access it. In fact, billions of people are still digitally disconnected, as bringing connectivity to certain zones does not make a good business case. The only solution for these unsatisfied potential users is to directly undertake the building of the infrastructure required to obtaining access to the Internet, typically forming groups in order to share the corresponding cost. This article presents a global classification and a summary of the main characteristics of different Alternative Network deployments that have arisen in recent years with an aim to provide Internet services in places where mainstream network deployments do not exist or are not adequate solutions. The "Global Access to the Internet for All" Research Group of the Internet Research Task Force, where all authors actively participate, is interested in documenting these emerging deployments. As an outcome of this work, a classification has converged by consensus, where five criteria have been identified and, based on them, four different types of Alternative Networks have been identified and described with real-world examples. Such a classification is useful for a deeper understanding of the common characteristics behind existing and emerging Alternative Networks.

Introduction

It is often claimed that the Internet is a part of our daily lives, but the reality is that in 2016 there were only around 3 billion Internet users in the world, out of a population of over 7 billion people. The reasons behind this lack of usage cannot be entirely attributed to limitations of infrastructure, as global satellite and mobile data coverage are widely available. It is estimated that over 5.5 billion of the world's population have access to 3G communications, yet 2.5 billion are not using the Internet [1]. Even though factors such as the lack of relevant content and inadequate digital skills among those offline are also responsible for this situation, it is widely acknowledged that the main reason for this gap is cost [2].

In this context, finding alternative deployment models that may reduce the cost of communications is a matter of urgent concern, as highlighted by the numerous relevant initiatives worldwide, including the Global Connect Initiative (https://share.america.gov/globalconnect/); Internet for All (https://www.weforum.org/projects/internet-for-all); 1 World Connected (http://1worldconnected.org/); and the UN Internet Governance Forum 'Policy Options for Connecting and Enabling the Next Billion' framework (http://www.intgovforum.org/cms/policy-options-for-connection-the-next-billion). We note that a number of sessions at the latest Internet Governance Forum, convened by the United Nations in Guadalajara, Mexico, in December 2016, (https://igf2016.sched.com/) were devoted to the discussion of this issue.

The present article addresses this gap by presenting a survey of different alternative models identified through a consensus process achieved by the Internet Research Task Force (IRTF) Global Access to the Internet for All (GAIA) Research Group. This consensus crystallized in a Request for Comments on "Alternative Network Deployments" that this article summarizes [3]. Alternative Networks are considered those that share some of the following characteristics:

- They have a relatively small scale.
- They may follow de-centralized approaches.
- The investment in infrastructure may be low, and may be shared by independent users, commercial and non-commercial entities.
- Users may be involved in the design, deployment, maintenance and daily operation of the network.

In particular, we explain the criteria and present a classification of Alternative Networks into four distinct types, detailing the main characteristics of each one, as well as the technologies they rely on through real life examples. To the best of our knowledge, this classification does not exist in the literature and provides a guide to people interested in non-traditional deployments, ranging from researchers to community members, and a set of references for further research into each of them.

In the next section, the key challenges that Alternative Networks aim to solve are discussed. We then present the classification criteria, detail the classification of Alternative Networks into four distinct types, and refer to emerging types of networks. Finally, findings are summarized.

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Digital Object Identifier: 10.1109/MCOM.2017.1600663

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Challenges that Alternative Networks Aim to Solve

Alternative Network deployments are nowadays present in every part of the world. Even in high-income countries, they are being built as an alternative to commercial networks managed by traditional network operators. Alternative Networks have emerged to provide Internet services to areas not covered by traditional operators due to high cost or challenges that commercial networks are ill equipped to solve. Such challenges range from privacy concerns to limited power resources or lack of technical expertise. In this work, we do not aim at providing an exhaustive list of these challenges. Instead, we focus on two key aspects that trigger the development and deployment of Alternative Networks: the digital divide and the differentiation of areas based on geography and user density.

Digital Divide

According to the ITU's report *ICT Facts and Figures* 2016 [1], half the people on Earth are still disconnected from the Internet. Furthermore, the connected population is unevenly distributed: while 84 percent of households are connected in Europe, in the African region only 15.4 percent of households are connected. The digital divide between "Global North" and "Global South" is based on information and communication technologies (ICT) factors such as:

- The availability of both national and international bandwidth.
- The difficulty to pay for the services and the devices required to access the ICTs.
- The instability (or lack) of power supply.
- The scarcity of qualified staff.
- The existence of a policy and regulatory framework that hinders the development of Alternative Network deployment models, favoring instead state monopolies or entrenched incumbents.

The uneven digital development state of a country may produce another form of inequality, which involves infrastructures, the ICT sector, digital literacy, legal and regulatory framework, as well as content and services. In this context, the concept of digital divide refers to the limitation or the total absence of one or more of these dimensions. This divide constitutes a new inequality vector that may simultaneously generate progress for some, while creating economic poverty and exclusion for others, as happened during the Industrial Revolution. It is undeniable that mobile network operators have certainly contributed to lowering the divide, but at the same time the model they follow for increasing connectivity has some restrictions that result in a limitation of the development outcomes. Furthermore, a significant part of the costly bandwidth may be spent on updates, advertising and other data not contributing to development or economic inclusion.

Thus, prices are still unaffordable to many people, as they may constitute an exaggerated percent of an individual's income, hindering one's willingness to invest in communications. Furthermore, the cost of prepaid packages, which are the most suitable option for informal economies, is high when compared with the rate of post-paid subscribers.

In this context, in November 2015, the World Summit of the Information Society called upon governments, the private sector, civil society and international organizations to work actively to bridge the digital divide by achieving "a people-centered, inclusive and development-oriented Information Society," allowing access for everyone to information and knowledge to achieve sustainable development and improve the quality of life.

Alternative Networks can be seen as a way for civil society and local stakeholders to become more active in the promotion of affordable alternatives to connect themselves to the Internet. Additionally, these networks can enhance other dimensions of digital development, such as increased human capital and the availability of localized content and services, fulfilling the specific needs of each local community.

Adverse Geography and Low User Density

The digital divide presented in the previous subsection is present in different countries, but also among different regions within a country. Such is the case for rural inhabitants, who represent more than half of the world's population. The disposable income of citizens in rural areas, with many surviving on a subsistence economy, is typically lower than those inhabiting urban areas. Additionally, a significant percentage of the disconnected population is located in geographies difficult to access and/or exposed to extreme weather conditions, sometimes even lacking electrical infrastructure. From a networking point of view, customers in rural zones are spread over a wider area and are typically located farther from the Internet access point compared to urban users.

As an example, Fig. 1a shows the mobile network coverage map in Johannesburg, while Fig. 1b depicts the two different zones, which can be defined as urban/suburban and rural. Figure 1a highlights the coverage variation between the connected urban/suburban areas in color and the rural areas with no coverage in white. The latter create an ideal niche for the deployment of Alternative Networks.

In rural areas, low population density discourages telecommunications operators from providing the services offered in urban areas due to lack of profitability. This situation has motivated residents and stakeholders of certain rural areas to become the owners of an Alternative Network deployment. The cost of the required wireless infrastructure to set up a network, including a proper power supply (e.g., via solar energy), is within the affordability range of many rural individuals or small communities. This means that they can share the cost of the infrastructure and the Internet gateway and access the network via inexpensive wireless devices. Some examples are presented in [4, 5].

Classification of Alternative Networks

The discussion within the GAIA Research Group started with the identification of the criteria to be used in the classification of the different types of Alternative Networks. Only then could we build a coherent classification of the existing networks, which have been divided into community networks, wireless internet service providers, shared infrastructure model, and crowdshared approaches. This section explains both the criteria and the classification,

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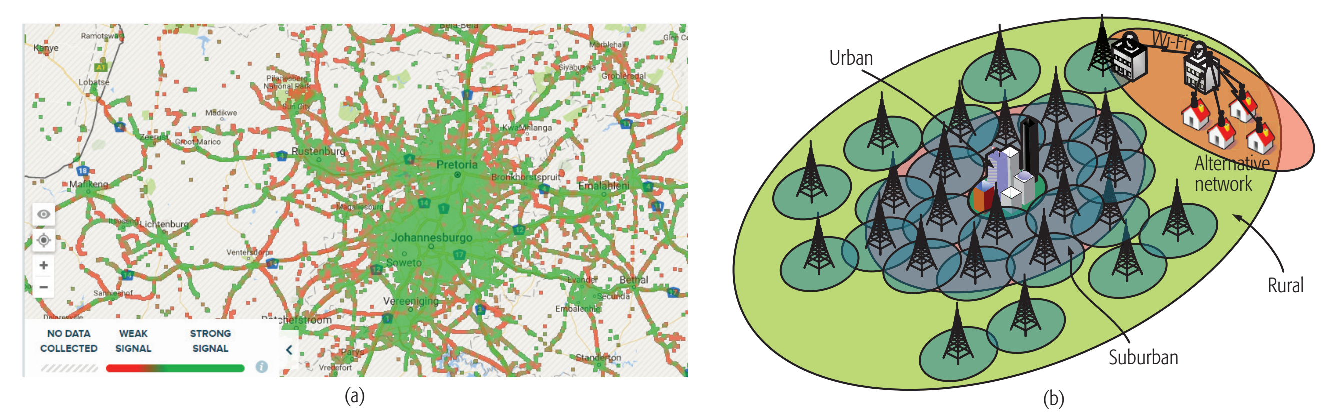

Figure 1. Urban, suburban and rural zones' network coverage: a) 2G/3G/4G mobile network coverage map in Johannesburg (http://opensignal.com/) (white color: no coverage; red color: weak signal; green color: strong signal); b) a typical Alternative Network deployment for an under-served rural area.

along with real examples. We conclude with a discussion of emerging Alternative Networks.

Classification Criteria

After a detailed study of existing deployments, and a long discussion within the IRTF Research Group, five criteria that differentiate existing Alternative Networks have been identified. We note that the criteria are not "fully orthogonal," as is obvious from the description of the different network types. In particular, the classification criteria include the following.

Entity Behind the Network: The entities or individuals that start, manage and push the network can be a public stakeholder, a community of users, or even a private company. Each of these entities can build and manage a network on their own or collaborate with each other, sharing network resources (e.g. "crowdshared" approaches). In Fig. 2, we depict the three possible promoting entities and showcase where the different types of Alternative Networks (detailed in the next subsection) fall.

Purpose: The purpose and benefits of Alternative Networks can be classified depending on their economic, political, social or technological objectives. Both the society as a whole and specific actors can enjoy the benefits provided by these networks, such as:
- Extending coverage to under-served areas (users and communities).
- Providing affordable Internet access for all.
- Reducing the initial capital expenditures (CAPEX) for the network, end user, or both.
- Providing additional sources of capital beyond the traditional carrier-based financing.
- Reducing ongoing operational costs (OPEX) such as backhaul, power provisioning or network administration.
- Reducing hurdles to adoption as digital literacy or literacy in general.
- Leveraging expertise and having a place for experimentation and teaching, including research purposes.
- Sharing connectivity, resources and local content.

As far as users are concerned, other underlying motivations may be present:
- Their desire for affordable sharing of Internet connectivity.
- The experience of becoming active participants in the deployment and management of a real and operational network.
- Raising awareness of political debates around issues like network neutrality, anti-censorship and more.

Administrative Model: The administrative model can either be centralized, where a single entity plans and operates the network, or non-centralized, where the network is managed following a distributed approach, in which a whole community may participate, including the enhancing of the network by the addition of new users.

Technologies Employed: Alternative Networks employ a variety of technologies to achieve connectivity, including optical fiber, femtocells, variations of WiFi, WiMAX and dynamic spectrum access solutions. Figure 3 depicts these technologies and the type of Alternative Networks where they are usually employed. Other options may exist, but the most common ones have been included in the figure.

Optical fiber has been used in cases where national service providers decline to bring connectivity to isolated villages, so the community decides to build their own fiber network. Such examples include Lowenstedt in Germany and parts of Guifi.net in Spain, which consists of more than 33,000 nodes [6].

Licensed mobile spectrum has also been exploited through the use of femtocells, i.e., small, low-power cellular base stations. Even though the paradigm of femtocells was conceived to improve indoor coverage, it has proven to be a feasible solution for bringing 3G coverage to under-served rural areas with low population density, as the number of users and the covered area are small enough to be managed by a low-cost femtocell. Moreover, if the community already owns an IP network for other purposes, sharing that infrastructure with the 3G operator as a low-cost backhaul may dramatically reduce the costs for the operator and make the service sustainable for small communities that could not be served otherwise [7].

IEEE 802.11 (WiFi) is by far the most popular standard in Alternative Networks; its different variants (a/b/g/n/ac/ad/af) use unlicensed bands, thus defying spectrum costs. The medium access control (MAC) is based on carrier sense multiple access with collision avoidance (CSMA/CA), and was designed for short distances, so modifications of MAC parameters are required for long distance links. Some of these modifications (e.g., WiFi over long distance (WiLD)) [8] are frequently employed in Alternative Networks. However, a modified contention MAC is still inefficient at long distances. Many manufacturers have developed alternative time division multiple access (TDMA) MAC protocols for long-distance 802.11-based products that can be activated as a CSMA/CA replacement on a per-link basis. As a result, low-cost equipment using these techniques can achieve high throughput even at distances beyond 100 kilometers.

WiMAX systems (IEEE 802.16-compliant) over non-licensed bands have also been employed in certain cases. WiMAX can enable usage at distances up to 50 km while achieving high spectral efficiency [9].

Finally, nowadays there is an increasing interest in exploiting TV white spaces in regions where parts of the VHF and UHF spectra are unused, by means of dynamic spectrum access solutions. There are emerging technologies that detect those unused fragments of the spectrum by jointly sensing and querying spectrum databases, so they can be leveraged by secondary users with no harmful interferences to primary users. Cognitive radio techniques permit the dynamic adaptation of the transmission power, modulation and frequencies, as required by these solutions. The two dominant standards for TV white spaces are IEEE 802.11af (specifically adapted from 802.11) and IEEE 802.22, designed for long-range rural communication.

Typical Scenarios: Based on the challenges described above, Alternative Networks can be found in urban/suburban and rural areas of both "Global North" and "Global South" countries, although some types of networks are more typical in certain zones.

Common Types of Alternative Networks

Having defined the classification criteria, we present a classification of Alternative Networks. Four different types of networks have been identified, explained in detail below, including some real-world examples for each one. Table 1 summarizes the characteristics of each type of network.

Community Networks: Community Networks are large-scale, self-managed networks that are built and organized in a non-centralized and open manner. As participation in a Community Network is open, they grow organically, since new links are created every time a host is added. This is done via the sharing of an open peering agreement among all members, with the common objective of freely connecting them and increasing network coverage. In this sense, members of a Community Network are not only users, but active contributors to the network. In most cases, members keep ownership of the part of the infrastructure they have contributed to build. Thus, the network presents a high degree of heterogeneity with respect to the devices used in the infrastructure and its management. This results in increased entropy, as different protocols (e.g., routing) may be used in different parts of the networks. However, on the positive end, it allows the increase of the network size without incurring in major costs. One example that represents this model is Guifi.net [6], which has shown an exponential growth rate in the last decade, both in the number of nodes and end users. Figure 4a shows the structure of this network around Barcelona, Spain. As can be seen, the network covers both urban and rural areas, usually connected through long-distance links (the so called community mesh approach). In networks covering remote rural areas, tree and mesh topologies are frequent because they follow available terrestrial infrastructures such as rivers or roads that connect villages to the closest well-connected city. Figure 4b depicts a real network supernode used in Guifi.net, built using typical common off-the-shelf equipment, such as a Raspberry Pi.

Given that the ownership of the network is open and non-centralized, Community Networks incentivize the transfer of knowledge in order to maintain and expand the existing infrastructure. Another characteristic resides in the way community members organize themselves not only to control the usage of the network, but its operation as well, as certain tasks like IP addressing and routing require a minimum governance infrastructure. This participatory model has proven to be effective in connecting sparse populations, which

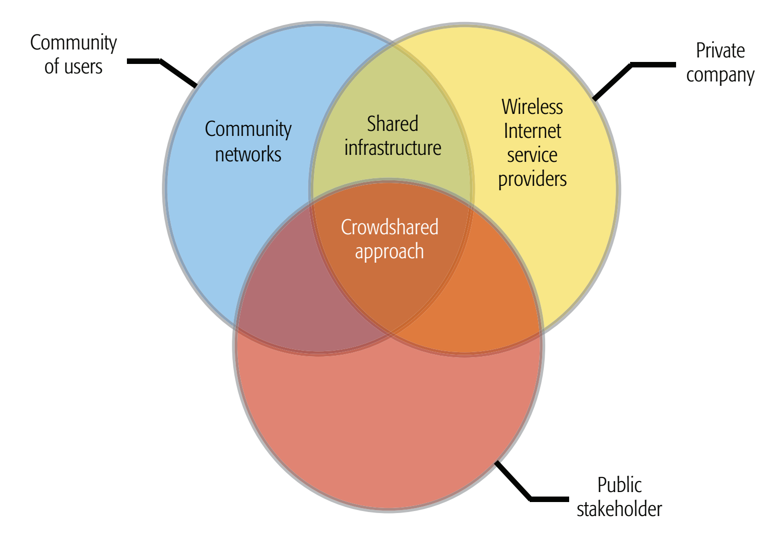

Figure 2. Entity behind the network and type of Alternative Network.

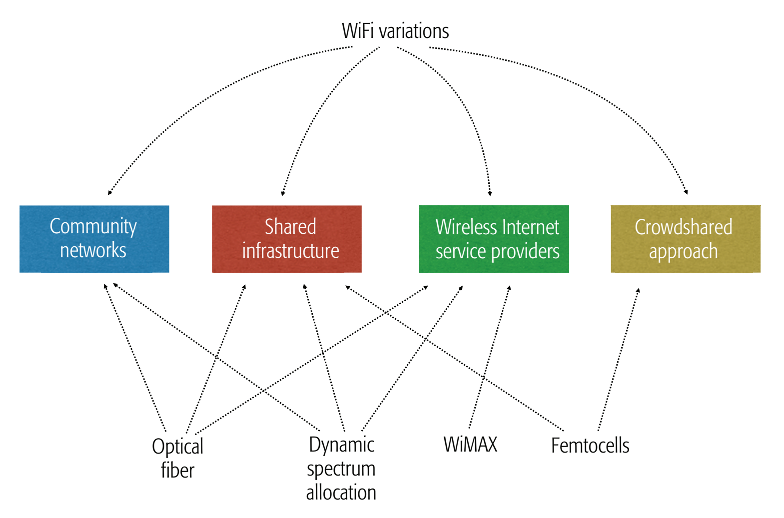

Figure 3. Employed technologies and type of Alternative Network.

	Entity behind the network	Purpose	Administrative model	Technologies employed	Typical scenarios
Community networks	Community of users	All goals mentioned above	Non-centralized	WiFi variations Optical fiber Dynamic spectrum allocation	Urban/suburban and rural
Wireless Internet service providers (WISPs)	Private company	To extend coverage to underserved areas To reduce CAPEX To provide additional sources of capital	Centralized	WiFi variations Optical Fiber WiMAX Dynamic spectrum allocation	Suburban and rural
Shared infrastructure model	Community of users Private company	To eliminate a CAPEX barrier for operators To decrease the OPEX being supported by the community To extend coverage to underserved areas	Non-centralized	WiFi variations Optical fiber Femtocells Dynamic spectrum allocation	Rural in "Global South" countries
Crowd shared approach	Community of users Private company and Public stakeholder	To share connectivity and resources	Non-centralized	WiFi variations femtocells	Urban/suburban and rural

Table 1. Alternative Networks: characteristics and classification.

is key for the enhancement and extension of digital Internet rights. This participatory model also plays a role in the range of services offered by a Community Network, which can be used as a backhaul for services that are either completely free or commercial, depending on the preferences of their members.

Wireless Internet Service Providers (WISPs): Wireless Internet Service Providers (WISPs) are commercial entities that use wireless technologies in order to create the infrastructure required to provide Internet and/or Voice over IP (VoIP) services. They are common in areas not covered by traditional operators. WISPs mostly employ wireless point-to-multipoint links using unlicensed spectrum. However, these bands face challenges in some places, either for the overcrowding of such spectrum, which compromises the quality of service, or where the regulatory framework forbids its use. In these cases, WISPs are resorting to the use of licensed frequencies.

Local companies operate most WISPs, responding to a perceived market gap. Nevertheless, a non-negligible number of WISPs, such as AirJaldi in India, have expanded from local service into multiple locations. For the past decade, most WISPs using cloud-managed solutions have been in the "Global North" markets. In 2014, a similar cloud-managed service initiative, aimed at the "Global South" markets, appeared; Everylayer uses a proprietary cloud-based platform to coordinate low-cost WiFi and fiber optic high-speed last mile connections.

Shared Infrastructure Model: Because of the low returns expected, operators may be reluctant to deploy network infrastructures in large, sparsely populated areas. This happens when the usual model is followed, in which a mainstream operator deploys and owns the infrastructure, or rents it to/from other companies. However, if a community of users already owns a network infrastructure (e.g., connecting a public building, a medical dispensary, and so on), it can be shared with an operator, resulting in a win-win scenario. On the one hand, the operator significantly reduces their initial investment, as CAPEX is mainly associated with the deployment of the access network, in exchange for a small increase in the OPEX caused by the renting of the infrastructure. On the other hand, the users gain access to telecommunications services, and get some income from the operator, which can be used for maintaining and improving their network. Although this kind of win-win situation could happen in any country, it is typically found in rural areas of the "Global South" where no universal service regulations are in place. In cases where incumbent operators were reluctant to deploy rural infrastructures because they did not find it profitable to serve small rural communities, communities or their local institutions deployed their own infrastructures, often with public funds or support from development agencies.

One example of this model is the deployment of 3G infrastructure in rural areas where a broadband community network was already in place. In these cases, placing a femtocell in close proximity to the community and sharing the Internet backhaul connection benefits both the users (by obtaining low-cost 3G coverage) and the operator (by avoiding the costs of deploying new infrastructure). Real use cases have been described in the European Commission FP7 TUCAN3G project, which deployed experimental testbeds in two regions in the Amazon forest in Peru [9]. In these networks, the operator and several rural communities cooperated to provide services through rural networks built up with WiLD links.

Crowdshared Approach: This type of Alternative Network corresponds to a set of WiFi routers whose owners share common interests (e.g., sharing connectivity, resources or peripherals) regardless of their physical location. Crowdshared approaches conform to the following idea. A home router hosts two wireless networks, one for serving the owner, and another for public (shared) access, offering a small fraction of the bandwidth to any user of the service in the immediate area (some examples are described in [10]). A governmental initiative corre-

(a) (b)

Figure 4. (a) Structure of Guifi.net around Barcelona (Spain); (b) junction box of a guifi.net supernode (Spain), including a Mikrotik wireless router, a Raspberry Pi used as proxy, and the router of the operator connecting to the Internet.

sponds to the networks created and managed by city councils (e.g., [11]), which act as virtual network operators (VNOs). Other entities that act as VNOs can be grass root user communities, charities, content operators or smart grid operators.

Similarly, some companies (e.g., FON and Vodafone) also promote the use of WiFi routers with dual access (a dedicated WiFi network for the owner, and a shared one for public access). After having a community of users sharing their routers, the members of this community can share their connection and, in turn, get access to all other community resources. In some cases, the owners of the Internet connection can benefit from the temporary leasing of their equipment to nomadic users that connect to WiFi access points. Some other users outside the community can pay passes to gain network access.

Traditional network operators have a financial incentive to lease out the unused capacity at a lower cost to the VNOs, producing revenues for both the VNOs and the sharers [12]. Thus, an incentive structure is created for all actors: end users get money for sharing their network, and network operators are paid by the VNOs, who in turn accomplish their socio-environmental role. Some mainstream operators ship their routers with pre-installed crowdsharing functionality to ease the community formation process.

Emerging Alternative Networks

In addition to the aforementioned classified types of networks, Alternative Networks can also emerge as side-effects of other activities. Some networks that were started by academic entities as research testbeds [13] resulted in non-centralized networks partly governed by regional entities [14].

In a similar way, some rural electric cooperatives have ended up providing broadband access to their users through fiber [15]. These cooperatives started in the 1930s with the aim of providing electric power to the dwellers of remote farms in some zones of the United States. Nowadays, the problem is quite similar, but related to connectivity instead of electricity: investors may be reluctant to deploy an infrastructure to serve a limited number of users. Certain cooperatives installed fiber for running smart grid applications, but later noticed that the same fiber can be used to connect their customers to the Internet.

More recently, the challenge of Internet access provisioning for remote areas has proved fertile ground for innovation. A decade ago, research on delay-tolerant networking led to the creation of DakNet, a network that provides Internet connectivity in a delay-tolerant fashion using buses as mechanical backhaul. Along the same lines, low altitude satellites, drones and balloons are nowadays being considered as means to provide Internet access to remote areas, but these solutions are still at the research level and have not yet been deployed in a real functional Alternative Network.

Conclusions

This article has presented a global classification and a summary of the main characteristics of Alternative Network deployments, which have arisen with the aim of getting more people connected to the Internet. In particular, we have identified five classification criteria and proposed a classification of Alternative Networks into four distinct types. For each type, we detail the main characteristics, describe the technologies they rely on and present real-life examples. To the best of our knowledge, this is the first time a classification of non-traditional network deployments has been proposed. It has been elaborated within the Global Access to the Internet for All Research Group of the IRTF. Its objective is to act as a guide for researchers and community members interested in alternative deployments, and it can help them identify common characteristics of these networks.

Acknowledgments

We would like to acknowledge the contributions of those who have participated in the discussions in the GAIA IRTF list, providing ideas based on their experience and knowledge about Alternative Networks. Arjuna Sathiaseelan and Andrés Arcia-Moret were funded by the EU H2020 RIFE proj-

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ect (Grant Agreement no: 644663). Jose Saldana was funded by the EU H2020 Wi-5 project (Grant Agreement no: 644262). Javier Simó-Reigadas was funded by the EU FP7 Research Project TUCAN3G IST-601102 STP and the TEC2013-41604-R Project, funded by the Spanish Ministry of Economy, Industry and Competitiveness.

References

[1] International Telecommunications Union, "ICT Facts and Figures 2016," available: http://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2016.pdf, accessed 22 Dec. 2016.

[2] Alliance for Affordable Internet, "Affordability Report 2015-2016," available: http://a4ai.org/affordability-report/, accessed 22 Dec. 2016.

[3] J. Saldana *et al.*, RFC 7962, "Alternative Network Deployments, Taxonomy, characterization, technologies and architectures," Working Group Document in the IRTF GAIA (Global Access to the Internet for All) group, Aug. 2016; available: https://www.rfc-editor.org/info/rfc7962.

[4] E. Pietrosemoli, M. Zennaro, and C. Fonda, "Low Cost Carrier Independent Telecommunications Infrastructure," *Proc. 4th Global Information Infrastructure and Networking Symposium*, Choroni, Venezuela, 2012.

[5] B. Bernardi, P. Buneman, and M. Marina, "Tegola Tiered Mesh Network Testbed in Rural Scotland," *Proc. ACM Workshop on Wireless Networks and Systems for Developing Regions (WiNS-DR '08)*, ACM, New York, NY, USA, 2008, pp. 9–16.

[6] L. Cerda-Alabern, "On the Topology Characterization of Guifi.net," *Proc. IEEE 8th Int'l. Conf. Wireless and Mobile Computing, Networking and Communications (WiMob)*, 2012, pp. 389–96.

[7] K. Heimerl *et al.*, "The Village Base Station," *ICTD 2013*, Cape Town, South Africa, 2013.

[8] J. Simo-Reigadas *et al.*, "Modeling and Optimizing IEEE 802.11 DCF for Long-Distance Links," *IEEE Trans. Mobile Computing*, vol. 9, no. 6, 2010, pp. 881–96.

[9] J. Simo-Reigadas *et al.*, "Sharing Low-Cost Wireless Infrastructures with Telecommunications Operators to bring 3G Services to Rural Communities," *Computer Networks*, Elsevier, 2015.

[10] A. Sathiaseelan *et al.*, "A Feasibility Study of an In-the-Wild Experimental Public Access WiFi Network," *Proc. Fifth ACM Symposium on Computing for Development (ACM DEV 5)*, San Jose, 2014, pp. 33–42.

[11] T. Heer *et al.*, "Collaborative Municipal Wi-Fi Networks — Challenges and Opportunities," *Proc. 8th IEEE Int'l. Conf. Pervasive Computing Communications Workshops (PERCOM Workshops)*, 2010, pp. 588–93.

[12] A. Sathiaseelan and A. J. Crowcroft, "LCD-Net: Lowest Cost Denominator Networking," *ACM SIGCOMM Computer Communication Review*, 2013.

[13] V. Samanta *et al.*, "Metropolitan Wi-Fi Research Network at the Los Angeles State Historic Park," *J. Community Informatics*, North America, 2008.

[14] C. Rey-Moreno *et al.*, "A Telemedicine WiFi Network Optimized for Long Distances in the Amazonian Jungle of Peru," *Proc. 3rd Extreme Conf. Communication: The Amazon Expedition, ExtremeCom '11 ACM*, 2011.

[15] C. Mitchell, "Broadband at the Speed of Light: How Three Communities Built Next Generation Networks," Washington, DC: Institute for Local Self-Reliance and the Benton Foundation, 2012.

Biographies

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Andrés Arcia-Moret (andres.arcia@cl.cam.ac.uk) has been an associate professor in computer systems engineering at the University of Los Andes, Mérida, Venezuela since 2002. He obtained his undergraduate degree (with honors) and his Master's in computer science at the University of Los Andes. He also holds a Ph.D. in computer engineering from the Institut Mines-Telecom (Telecom Bretagne), France. He has been a guest researcher at the IRISA/CNRS in Rennes (France), in the Guglielmo Marconi Laboratory at the International Centre for Theoretical Physics in Trieste, Italy, and in the Computer Laboratory of the University of Cambridge, UK. His research is aimed at wireless networks, alternative network deployments and systems design.

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