future internet

MDPI

Article

A Decision Framework for Choosing Telecommunication Technologies in Limited-Resource Settings

Suzana Brown [1,*] and Alan Mickelson [2]

1 Department of Technology and Society, SUNY Korea, Incheon 21985, Korea
2 Department of Electrical, Computer and Energy Engineering, University of Colorado Boulder, Boulder, Colorado, CO 80309-0425, USA; alan.mickelson@colorado.edu
* Correspondence: suzana.brown@sunykorea.ac.kr; Tel.: +82-10-438-98900

Received: 31 October 2017; Accepted: 10 January 2018; Published: 12 January 2018

Abstract: Remote areas with sparse population, disaster areas in the aftermath, and refugee camps all require communication that is not forthcoming from commercial vendors. Numerous communication system options are available, but with widely varying cost and efficacy. The goal of this work is to discuss a framework in which to consider appropriate telecommunications technology. The framework approaches sustainable development as a business, under the assumption that social/technical/environmental sustainability requires economic sustainability. The framework incorporates well known and accepted business canvas as a roadmap. Information and Communication Technology (ICT) interventions are then considered in terms of their value proposition, markets, and perhaps most important for the realm of sustainable development, the key partners. To illustrate how the framework applies, we consider three case studies and then apply the resultant principles to the consideration of these ICT projects. The case studies are chosen for their diversity. Furthermore, after verifying the decision framework, recommendations are made for three ongoing intervention projects in limited-resource settings.

Keywords: long distance Wi-Fi; TVWS; limited-resource settings; business canvas

1. Introduction

Digital communication has revolutionized electronic communication that people use for their needs [1]. Unfortunately, not all people have benefited from this improvement. A chasm has opened between populations that can afford the broadest bandwidth communication, and those that either cannot afford access or have no access. Development scholars call this chasm the digital divide [2]. The state of local communication infrastructure has become a legitimate measure of development and the potential for development. Any development intervention requires assessment of the communication technology in the considered community [3].

A development practitioner has different goals when planning broadband deployment from that of telecommunications company employee [4]. The practitioner does not consider the potential for future revenue growth as a primary concern. More important is the community's ability to cover installation and maintenance costs, and whether there is potential long-term sustainability with some level of growth. The development practitioner does not consider infringement of patent or the appearance of competition to be problematic. The practitioner welcomes growth, especially if that growth originates in the community itself [5].

In this context, sustainability is defined as development that provides not only present but also future growth to a low-resource society [6,7]. Another trend differentiated by their sustainability is a community network movement that has evolved as a mosaic of systems that defends the basic human right to Internet access. A survey paper [8] presents a multitude of cases from Europe, Mexico, South Africa and Thailand.

Data from developing countries indicate a positive impact of telecommunications on national output, even when corrected for the effects of capital and labor [9,10]. The purpose of this study is to establish a decision framework for choosing which type of telecommunication technology to be used in rural and limited-resource settings. In the process, we distinguish between commercial and non-commercial providers, and regulated and unregulated frequency spectra. Finally, we show the validity of the framework on three distinct case studies, as well as make recommendations for the three studies still in the design stage.

In addition, throughout this work, we will assume that the development is being carried out in a region without a local carrier, or where the local carrier will cooperate with the development entity. With time, local carriers penetrate even the most rural and limited-resource locations. The need for communication with family, friends, employers, government, and others generate revenue in areas inhabited by even the poorest population.

If an area has a cell phone carrier, then any other entity (for profit or non-profit) cannot compete with licensed carriers unless they also become licensed carriers and bear the cost of national and international laws, regulations, and standards. Costs for a private network would include paying for a feed to the nearest internet provider who will sell bandwidth; or alternatively building a network, maintaining the network, and paying for licensing if necessary. Providing service for pay requires a different set of licenses than the licenses required for transmitting on a given frequency. Competing with a local carrier may also drive up the cost of purchasing an access point from that or another carrier. When there is a carrier but no high-speed internet, it is possible to work with the carrier and government in question. Public-private partnerships (PPP's) for broadband are ongoing in many parts of the world, but require political as well as commercial agreements. Governments generally want to push forward broadband deployment, even when the industry cannot do so, due to economic constraints.

In areas where there is not enough population density to generate the revenue necessary for economic viability for commercial cell phone carriers, either satellite or private networks are alternatives. Satellite service is generally expensive (https://www.globalcomsatphone.com/hughesnet/satellite/costs.html) because it costs a considerable amount of money to design, construct, launch and monitor a satellite. Private networks, though, must not only obey all the regulations governing public utilities, but also maintain all their equipment. Most transmission frequencies, for example, are regulated and require licenses, so licensing may be an additional cost. Television White Space (TVWS) is regulated worldwide [11], and licenses must be obtained to operate such equipment, even for non-profit services. In response to the need to bring connectivity in low-resource settings Wi-Fi long distance (WiLD) technology was developed from the remnants of the National Science Foundation Net [6]. Our framework considers two widely used approaches, WiLD and TVWS in limited-resource settings.

The major contribution of the present work is to give a roadmap for decision makers to make the most efficient choice when faced with various options for implementing a telecommunications technology in low-resources settings.

The rest of the paper is organized as following: Section 2 presents related work; a decision framework is presented in Section 3; in Section 4 a proposed framework is verified using multiple case studies, each with an existing network; in Section 5 three case studies in the design stage are evaluated and a solution based on the proposed framework recommended; Section 6 concludes the paper.

2. Related Work

In this section, we provide a short description of related work and identify the gap that the current paper closes. Most of the research papers look exclusively at the technical aspect of different technologies in limited-resource settings but few propose a specific framework when choosing among alternatives in different situations.

2.1. Studies on Comparison of Different Telecom Technologies

In a study by Nandi et al. [12], the authors focus on the different aspects of providing last-mile rural telecommunication access considering interfering factors, technology options, and deployment trends. Their choice of contributing factors includes geographic location, economic conditions, motivation and adaptability, and sustainable business framework. Technology options considered are wired and fixed wireless. Development trends are long-reach Wi-Fi, cellular, WiMax, Long-term Evolution (LTE), delay-tolerant networks, cognitive usage of TV white spaces, power line communications, MIMO wireless networks, and other methods such as Zigbee, and combinations of the above technical approaches. They consider only purely technical aspects and provide no decision framework.

In a discussion of an alternative form of network coverage for rural villages by Anand et al. [13], the authors point out that coverage is often lacking in areas of low population density in impoverished rural areas of the developing world. The telecommunication giants seldom deploy expensive infrastructure in such areas. Their proposed solution is called VillageCell. VillageCell is a low-cost alternative to high-end cell phone networks. They show that call quality of VillageCell is good, and they discuss energy requirements, licensing issues, and integration into the existing rural-area wireless network.

A business approach was adopted by Mishra et al. [14] who gave specific cost estimates and demonstrated the business case for a Wi-Fi/CDMA450 network with nearly fully subsidized cellular handsets as end-user devices. The authors used the Akshaya Network located in Kerala, India as a specific case study to show that a wireless network using Wi-Fi for the backhaul, CDMA450 for the access network, and shared personal computers (PCs) for end-user devices have the lowest deployment cost. However, the authors did not compare their proposed solution to other solutions.

A spectrum measurement study [15] in the Dallas-Fort Worth metropolitan and surrounding areas proposes a measurement-driven band selection framework. The authors measure the white space and Wi-Fi bands with in-field spectrum utility measurements, revealing the number of access points required for an area with channels in multiple bands. They conclude that as more channels are available in the white space bands, fewer access points are required for a given area, and as such white space solution is superior.

In addition, there is extensive literature [16–20] regarding a design of networks in rural locations, mostly for health applications using solar energy and heterogeneous wireless networks. These solutions utilize network optimization in order to provide broadband in low-resource settings.

2.2. Studies on the Impact of Population Density

A link between population density and investment in infrastructure by telecommunications companies has been noted in the past. Indeed, there is a consensus that a higher population density is linked to more developed infrastructure. In developed countries, the population correlates with cellular network density [9]. Data from the Organization for Economic Cooperation and Development (OECD) have shown that, among the developed countries, those with large urban populations such as South Korea, Japan, France, and the Netherlands exhibit higher broadband penetration than those with a significant rural area, such as the United States and Canada [10].

One study that tested the link between population density and mobile infrastructure is by DeMaagd et al. [21]. They found that population density is not the whole story. They argue that there is also a correlation with the cost of investment. When financial markets demand higher interest on borrowing funds, telecommunications firms invest less in capital-intensive infrastructure. The study [21] conclusion is that both higher population density and favorable interest rates are required to drive investment capital expenditure (CAPEX). The cases considered in this study are those with a combination of low population density and/or a high cost of capital.

2.3. Current Paper Contribution

To our knowledge, there is no comprehensive analysis that considers a business framework for the choices of telecommunication technology in limited-resource settings. The main goal of this paper is to provide a framework to decision makers for the most efficient choice when faced with various options for implementing a telecommunications technology in a community with low resources.

3. A Decision Framework

3.1. Adopting a Business Approach

In the proposed framework the first step is adopting a business approach for the implementation case. For that, it is necessary to have a business model in mind. A business model is a sustainable way of doing business, where the sustainability is defined as a concept that allows an entity to survive over time and create a successful, even profitable, business in the long run [22]. A relatively new approach, called business canvas, recommends a template for developing new or documenting existing business model, and it is a visual chart with elements describing a value proposition, infrastructure, customers, and finances.

The business canvas as formalized by Osterwald and Blank [23,24] is a generally accepted methodology for developing start-ups [25] (see Figure 1). Generally, it is considered unverified until the value proposition can be supported by data from numerous interviews with customers. The verification is evidently time-dependent as are markets and partnerships. The business canvas then needs to be periodically or even continuously revisited.

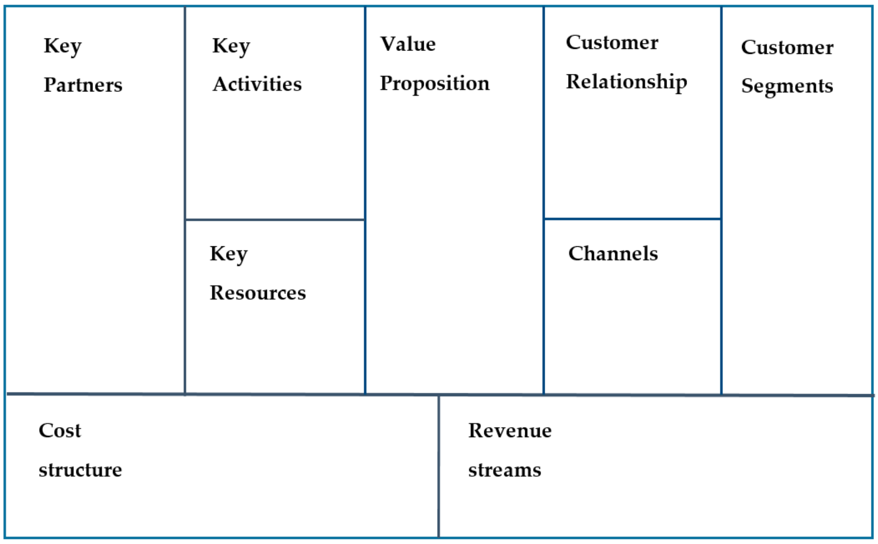

Figure 1. Business canvas.

For the purpose of our analysis we will split the Business canvas into two important sections:

(1) Value proposition (needs of a community), customers (who all can use the service), revenue (who will pay for the service).

(2) Key partners (carrier or no carrier) along with the key resources determine your cost structure.

The first part of the Business canvas will not be part of the current study and we will assume that it is developed prior to addressing the second part, which will be the topic of this section. In the second part regarding key partners, the only partners discussed presently will be the telecommunications providers. There are many other possible partners, among them notably is the University partner, which we discuss briefly in the first case study. However, such partners are commonly non-profit organizations, and as such have different goals from the commercial carriers.

As shown in Figure 2, for the choice of key partners, the situation decision makers are facing is if there is or not a local carrier. When there is a local carrier, it is difficult to compete with that local carrier without satisfying all national and international laws, regulations and standards. One possible situation that a carrier exists but it cannot provide enough bandwidth. Competing with the local carrier does not make business sense and if carrier can provide enough bandwidth the decision should be to purchase an access from that carrier. If the carrier cannot provide enough bandwidth it is possible to build a private network, following the path on the tree of no carrier.

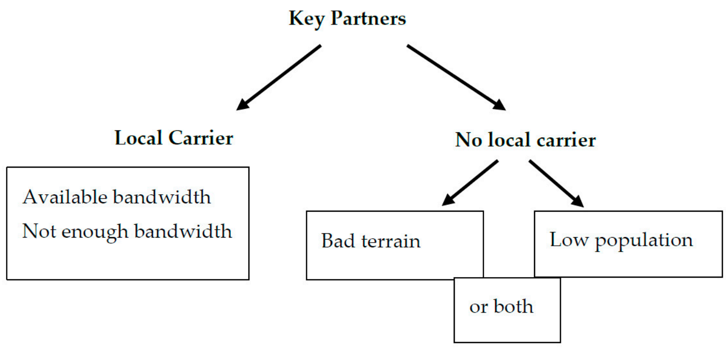

Figure 2. Key partners.

One example where there is a carrier, but no high-speed internet, comes from Dan Wessner who has been working for a couple of decades on such efforts [26]. Some other efforts based on public-private partnerships (PPPs) for broadband are ongoing in Africa (Botswana, South Africa, and Malawi) [27]. However, in such cases, it is important not to compete with the carrier because that would reduce the price of service and shrink the revenue.

There are places in the world where there are no carriers. When the population density of an area is low enough, carriers are not interested as they cannot recuperate investment costs. Such areas include Nepal, the Amazon (Peru, Brazil, parts of Ecuador), Indian reservations in the United States, Western New Guinea (within Indonesia), and numerous others. There are many such areas in Africa and some parts of Asia.

As discussed in Section 2.2, there is a consensus that in general higher population density is linked to more developed infrastructure. However, that condition has been proven only in developed countries [10]. In this study, we will argue that it holds in the developing countries also and that population density drives most cellular services providers to offer more affordable and better service. In circumstances of higher population density cellular infrastructure will develop organically and eventually have a lower cost than any other option.

Reasons for no presence of a local carrier could be either low population density or inhospitable terrain, for example, rugged mountains located in low-resource settings, or both. In both situations the most common choices are the following technologies:

1. TV white spaces (TVWS)
2. Long Distance Wi-Fi (WiLD)
3. Satellite

The choice between above technologies will depend mostly on the funding capabilities and the physical terrain. Physical environment, such as geographical layout is particularly important when deciding between using WiLD or TVWS, since WiLD networks are comprised of point-to-point wireless links that use high-gain directional antennas with a line of sight (LOS) over long distances (10–100 km) [28]. The cost differences are also a significant factor, mainly because WiLD does not require a license, while TVWS might.

3.2. Background on Telecommunication Technologies

It is important to keep in mind that different telecommunication technologies could be divided into two groups, commercial and non-commercial technologies, and then within each case, the technology could be operating in regulated or unregulated frequency spectrum, as shown in Figure 3.

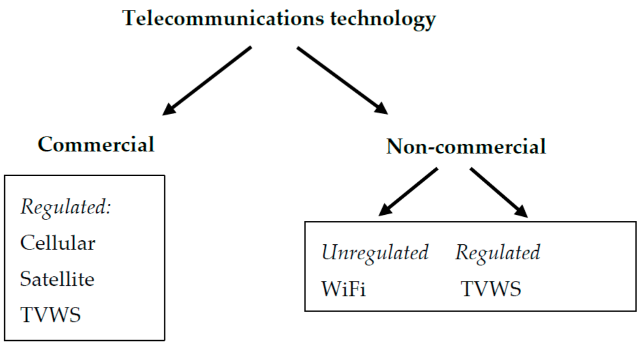

Figure 3. Telecommunications technologies.

To be more precise regulated and unregulated frequencies will be defined. Industrial, Scientific, and Medical radio bands (ISM) are unregulated in accordance to the United Nations agreement almost everywhere in the world. ISM operates in two frequencies: 2.4 and 5.8 GHz. On the other hand, TV White Spaces (TVWS) are defined (slightly differently in different places) to range from 54 MHz to 798 MHz (depending on the country). TVWS is almost completely regulated in most places around the world, and only ISM is unregulated everywhere by the UN agreement. TVWS does not overlap with ISM anywhere. Some slices of TVWS in some places may be unregulated, but not because of the UN agreement. If a slice of TVWS band is unregulated in one country, there is no reason to expect that the slice will be unregulated anywhere else.

Often Wi-Fi transmission has been chosen as a low-cost, long-distance access technology to bridge the digital divide. However, the important issue of planning such networks involves several sets of variables: the network topology, tower heights, antenna types to be used and the orientations, and radio transmit powers [29]. The original 802.11b standard gave rise to the now ubiquitous Wi-Fi router. Wi-Fi routers can be used inside or outside, but generally radiate and receive omni-directionally. Hence, high gain antennas applied to Wi-Fi transceivers give rise to Wi-Fi Long Distance technology. The idea of long-range Wi-Fi is simple. The power necessary for a 100 m broadcast translates to a 40 km station to station hop. A long-distance point-to-point link can then be affected by including two directional dish antennas per station in a chain of point-to-point stations spaced by less than 40 km.

There are numerous applications of WiLD technology, for example, mobile water sending with WiLD [30–32]. In addition, sustainable and successful WiLD networks have been implemented in the mountain areas of Nepal by the Nepal Wireless Networking Project [33,34], as well as the jungle areas of India [28,35] for treatment of eye disorders in rural populations.

TVWS uses bandwidth in the high-frequency spectrum (from 50 MHz to 700 MHz in the US and Canada, from 470 to 790 in Europe, while in other areas it varies according to national regulations [6]) that has previously been employed in analog television transmission. TVWS is a much lower information bandwidth than WiLDNet because of the lower frequency that also allows the waves to penetrate some amount of foliage. Microwaves above 1 GHz do not penetrate even individual leaves that are often of quarter-wavelength (resonant) dimension. There are commercial producers of white space solutions, although the cost is still quite high per bandwidth compared to other solutions. The regulatory situation for white space is complex. In most places, the spectrum is licensed, although the rules, fees, and power levels differ greatly from country to country. There are industry groups such as the Dynamic Spectrum Alliance (DSA) that promote regulatory changes on a country by country basis, as well as for international pronouncements by such groups by the International Telecommunications Union (ITU). In this respect, TVWS option has not yet been fully researched.

In relations to the proposed model, WiLD is a good choice in low population densities with or without rugged terrains, as long as there is a line of sight. TVWS could be a good choice in case of high population densities without a carrier.

3.3. Cost of Different Telecommunication Technologies

In this section we briefly discuss a cost for the three options in the proposed model: (a) TV White Space; (b) WiLD and (c) Satellite. Here are some examples of the cost/month/bitrate for each option:

- Long distance Wi-Fi is not regulated. There is no license charge if the transmitter power is below 30 dBm. Upfront costs vary depending on the bitrate. The complete cost of transceivers for up to 10 s of Mbps is $200. In some instances, antennas need towers, which increase the cost significantly. Maintenance is roughly half the price of upfront cost per year, not including labor. There is an additional cost for repairs and management.
- TVWS spectrum is regulated in most countries. In that case, licenses must be negotiated, and they are often expensive. Common upfront cost is around $4000 per transceiver for rates below 1 Mbps. It is very likely that no towers will be necessary, and that is an advantage, although this depends on the foliage density at the location. Maintenance is similar to Wi-Fi, including staff to maintain equipment and system.
- Satellite is usually the most expensive option and is rarely affordable in a development project. Even if satellite could be accessed without paying a large fee, it is not sustainable and would not make sense in the business approach that we propose.

In situations when there is a carrier, using the local carrier will have a cost/bps/month; however, maintenance cost will be significantly lower.

4. Evaluating Existing Networks

In order to verify the proposed model, we consider multiple case studies—three that have already been completed and three that are in the design stage. The purpose of the completed studies is to evaluate the gamut of possibilities. Recommendations are then made for the studies in the design stage.

The completed studies that are evaluated are:

- High Performance Wireless Research and Education Network (HPWREN) is the first WiLDNet of which we are aware. It connects universities with research centers while providing connectivity to Native American Reservations [36]. It is a highly heterogeneous mixture of private and public networks that is commercially viable.
- A pilot project carried by an American university in Rwanda and in coordination with the Ministry of Health (MoH) of Rwanda. The purpose for establishing the network was to collect health data. The network operated on the commercial cell phone system.
- NapoNet is a network that spans the Napo River of Peru providing service to 15 remote health posts. The Napo Network was funded by the Global Fund at a time when there was no commercial service available in this sparsely populated portion of the Peruvian Amazon. The only option was the most inexpensive private network transmission technology available in 2007.

The proposed framework presented in Section 3 will be used to evaluate the completed studies. The elements will include a different aspect of the business canvas such as value proposition and the choice of key partners.

4.1. HPWREN

The High Performance Wireless Research and Education Network (HPWREN) is an original Wi-Fi Long Distance network that is economically viable while functioning autonomously as a part of the

University of California San Diego (UCSD). This network was developed as an opportunity based on community needs. The development started in early 2000, and the need at that time was for the transmission of the rapidly increasing data output from Mount Palomar, an observatory with a large telescope collecting data, to computers where the data could be processed. UCSD arrays were already by that point generating much more data than could be stored, yet there was no high-speed internet in the mountains of Southern California at that time. There were some existing links from the defunct National Science Foundation Net program (NSFNET), and commercial networks through the Southern California suburbs, but there were also numerous rugged mountain areas and sparsely populated desert areas with no cell coverage.

In 1985, NSF funded a significant build-out of internet networking equipment in a 10-year program that is now known as NSFNET. A conclusion made by researchers in the program was that the government cannot compete with the private industry when it comes to problems that require a high initial capital expenditure (CAPEX). In 1995, NSF pulled out of NSFNET in favor of the private industry that was driving network expansion at that time. Owners of the equipment were not so quick to abandon what seemed like a very significant asset. Researchers at UCSD instead decided to apply the infrastructure to a problem that was both scientifically and commercially interesting, that of remote sensing over the internet.

HPWREN became a highly heterogeneous public-private partnership (PPP) that responded directly to the existing needs. Soon after the first implementation of ISM band Wi-Fi, researchers and developers realized that coverage of 4 pi steradians for a limited range could be converted to long range (up to 40 km) for a diffraction-limited 2.4 GHz beam carrying a broadband information stream. The 40-km range of original WiLD was enough to move relatively large bandwidths from mountains to suburbs, but the suburban transmission was not as easy as transmission through open space. The network then used WiLD links where possible and leased from commercial networks where necessary. The network linked villages on Indian reservations with data-intensive links to astronomical facilities, together with commercial traffic, to generate an economically viable network that simultaneously served as a testbed. The network ranges from Southern California, from the southern edge of Orange County to the Mexican border and from the Salton Sea on the east to its hub at University of California at San Diego, with some links to the barrier islands to the west.

From the perspective of the proposed decision framework, HPWREN has used local carriers whenever they could and built a private network to close the gap in connectivity.

4.2. Rwandan Health Pilot Project

Carnegie Melon University (CMU) Africa in Rwanda runs a graduate program in Information and Communications Technology (ICT) and attracts high-quality faculty by capitalizing on research opportunities that are multitudinous in the rapidly expanding Rwandan economy. The health service in Rwanda is plagued by a low patient-to-doctor ratio and a lack of well-trained medical personnel [37]. Electronic communication offers streamlining of service provision that could be advantageous to the Rwanda National Health Service, as well as lucrative to international healthcare providers. The Rwandan health pilot project under discussion here was executed by CMU Africa and funded by a multinational healthcare company (Ricoh) to learn about the pros and cons of electronic record keeping in a developing world environment.

This pilot project was performed in cooperation with the Rwandan Ministry of Health (MoH) and Kibagabaga hospital. In response to health burdens, Rwanda initiated a reform of the national community health system, which was initially implemented in 1995 [38], including Community Health Workers (CHWs), who are major participants in the Rwandan health system that provides preventative and curative healthcare services. Therefore, the project involved CHWs from Gasabo district, one of the most populated districts in Rwanda with approximately half a million people (http://statistics.gov.rw/publications/2012-population-and-housing-census-provisional-results). The study tested a hypothesis that CHWs could use smart phones for health data collection; a mobile application was installed on a smart phone, and given to 24 Rwandan CHWs to monitor children's growth and development. The research question was whether CHWs with no more than secondary school education could operate an electronic record keeping system that would actually save doctors and health workers time and effort in the long run.

An initial decision made by the researchers was to implement the electronic record keeping system using the existing cellular network. There is an extensive cell service throughout the capital (Kigali) and its suburbs. Although the power system is unreliable, the cell system (as in most parts of the world) is required to run independently of the power grid. In addition, the Rwandan top cellular provider, MTN, has network area coverage of 99%, with a footprint that is covered by 4G, 3.75G, and EDGE networks, as well as an extensive fiber network. With the support of the MoH of Rwanda, who has an excellent collaboration with MTN, it was possible to obtain greatly reduced prices for 3G networking time. Time delay tolerance was built in to the smart phone data collection program so that servers that were disabled due to temporary power outages did not pose a problem for system operation. CHWs were able to learn how to use a specially devised mobile application for data collection, and using the cell network, upload the results to a centralized server were data was served for subsequent analysis.

The system was implemented as a pilot in 2014–2015. The pilot was successful in demonstrating that using modern electronic tools for health data collection allows better tracking of health indicators [39]. Because of the extent of the cell network, the system could be expanded to nearly nationwide with little change. Finding funding for continued operation in a cash-strapped economy has been a problem, despite the Rwandan impressive economic growth of 8% per year [40].

For this project, a choice was made to collaborate with the existing carrier, and that choice was in accordance to the argument made about key partners, related to the business canvas discussed in Section 3.

4.3. NapoNet

At the turn of the millennium, the 450 km of the middle and upper Napo River of Peru was without almost without health services or schools. There had previously been no communication infrastructure along the river. A satellite company (GILAT) had installed communication centers in some of the villages. The centers never became popular. The communication network that was championed by the Enlace Hispano Americano de Salud (EHAS) was funded in part by the Global Fund and in part by the City of Madrid. The network was designed to link the 15 Napo River health posts with the Peruvian Health service in Iquitos. As Iquitos is linked with the rest of the world by microwave links carrying internet, a head-end in Iquitos then could have the additional benefit of linking the Napo to the World Wide Web. Without existing infrastructure, there was no choice but to build a broadband private network. The most cost-effective transmission medium per bandwidth at the time was WiLDNet, as implemented over IEEE 802.11g.

NapoNet was constructed in 2006 and 2009. It has been continuously upgraded since that time from 802.11b to g, n to ac. A problem with the network has been the strict rules under which it was built. The network was designed for transmitting health data with no stipulation for generating revenue. Ownership and operation of the network then passed from the Global Fund to the Health service of Peru at the completion of the PAMAFRO (Control de la Malaria en las Zonas Fronterizas de la Región Andina: Un Enfoque Comunitario or the Pan Andean program for Malaria Control in frontier areas) project in 2014, without a revenue source other than the state, and the network has struggled to keep operations going. The network has been used a testbed for new technologies as funded by the European Union among other means of preservation.

The main problem of this network is that there is no value proposition, no less a validated value proposition. In the case of NapoNet, EHAS saw an opportunity. The PAMAFRO project offered an opportunity to EHAS to be involved in a near state of the art network in a region where there was no other communication. Stipulations in the original contract were that control of the network must revert to the Health Service of Peru after completion of the PAMAFRO project.

In order to build the network, EHAS obtained funds from the Global Fund and from the Town Hall of Madrid. There is some provision for maintenance of the network in the annual budget of the Health Service, but no provision was made for the network to engage in any revenue-producing activity. The subsequent (to 2014) operation of the network has been characterized by down times due to maintenance issues. In the light of the proposed framework, this project is an excellent example of a situation with no business approach and no paying customers.

5. Networks in the Design Phase

Next, three case studies in the design stage are evaluated and a solution based on the proposed model recommended. The three case studies include a network for education in Papua New Guinea (PNG), a network to be operated by Kepler University in a Rwandan refugee camp called Kiziba, and an extension of a network linking together health posts in the Altiplano of Bolivia, Camacho Net.

5.1. Camacho Net

The Camacho Net project was initiated by an award from the IEEE Humanitarian Technology Challenge (HTC) in 2011. This ICTD project focused on providing broadband links between health posts in the Altiplano of Bolivia northeast of La Paz, Bolivia, along the eastern bank of Lake Titicaca. The area is one of the most remote and sparsely populated in the world. The surface of Lake Titicaca lies at an elevation of 3800 m. The mountains farther east peak at well above 6000 m.

The initial system was configured in 2014 and it links health posts in Chaguaya, Carbuco, and Challapata. However, the funds for the link to the regional hospital in Escoma and the northern port town of Puerto Acosto were not released in 2014. CamachoNet is a new name, for this previous HTC project is expected to be initiated in January 2018 with funds from IEEE. The network is planned to include the Escoma hospital, as well as health posts in Puerto Acosto and Humanata. The Chaguaya, Carbuco, and Challapata network is still functioning and has been credited as being a primary reason for several lifesaving surgeries on accident victims that could not have taken place without dedicated communications between health workers.

There is a local cell phone carrier in the region. Broadband can be purchased from the carrier, but the prices are exorbitant and no price moderation is possible in the near future, in part due to the scarcity of population in the region. A private subscription network could be devised that does not compete with the present carrier. A for-profit company was formed from the University volunteers from La Paz who constructed the original network in tight collaboration with the communities in question. Agreements with the communities are being updated and new agreements with local entrepreneurs who have ideas for services that are not in direct competition with carriers are also being developed.

5.2. Papua New Guinea

A network has been proposed as a means of distributing learning materials to primary and secondary schools, as well as offering IEEE educational courses to community members in an area surrounding a plantation in Madan, a Western Highlands province of Papua New Guinea (PNG). Madan is located 20 km east of Mount Hagen, 1 km north of the Highlands Highway and 20 km west of the border with Jiwaka Province. The network, centered on the plantation owner's house, is to include 35 schools and a health center, all located within a 10 km radius [41]. WiLDNet is under consideration as a technology.

The Western Highlands of PNG is the most heavily populated density of roughly 90 per square km. The area in question is even more densely populated (135/km^2), although is poor, with an average income barely above the chronic poverty level. The area is served by a 3G provider that employs low orbit, low latency satellite linkage. Most of the Highlands province is limited to 2G services, but the wealthier population near the Highlands Highway deems 3G provisioning economically viable. The 3G is sufficiently robust so as to provide hot spot service that will support Skype and other videos.

The value proposition is that schools would be willing to pay for dissemination of learning materials, and that community members will pay for postgraduate learning opportunities. The only partner that has so far been considered is the Madan Plantation on which the equipment is to be located. No discussions with government, communities, or 3G providers have yet been initiated. According to the proposed framework, collaboration with the local carrier would be the most efficient choice.

5.3. University in Kibiza Refugee Camp

Established in 1996, Kiziba refugee camp is located about 15 km outside Kibuye town in the Karongi District, in the western province of Rwanda. It is a home to a total of 17,270 people of concern, who are assisted by the United Nations High Commissioner for Refugees (UNHCR) agency and other humanitarian agencies. One of the pressing issues in the camp is education. The Kiziba camp education program included only one school, which went through Senior 3 (equivalent to ninth grade in the US). To graduate from secondary school, students had to find a scholarship or other means to attend school outside of the camp. From primary to secondary school, many agencies and government departments work hard to ensure students have access to education in Kiziba. After that, it becomes challenging. Opportunities for higher education or long-term employment were almost nonexistent for refugees, outside of a few positions within non-governmental organizations, which were particularly difficult for Kiziba's female residents to access. In response to the proven demand and clear need for tertiary education, Southern New Hampshire University (SNHU) College for America developed and proposed a Kiziba pilot program, naming it Kepler Kiziba. Population density in the camp is low, and currently the university has only 100 enrolled students. Kepler University in Kiziba camp provides students with laptops and access to the Internet. Students access educational material online and earn associate and bachelor's degrees.

Current infrastructure includes access to a cellular network of the third largest telecom provider in Rwanda, Airtel. Kepler Kiziba technical staff reports several existing challenges. At the top of their list was the lack of Internet bandwidth, which is made worse by intermittent quality of service (QoS) issues, a common challenge in developing countries. The camp students currently receive speeds of 10 Mbps, with the capability to expand to 50 Mbps. Congestion occurs only during hours that students are in the classes, which are running from 2 to 6 p.m. The study room for students is open until 10 p.m. since they are not allowed to carry laptops "home". Kiziba currently pays more than $815 US per month for internet access. Streaming of media content is unreliable, even in the capital of Rwanda, Kigali, so Kepler students do not stream live lectures. This feature is desirable for the future, however, and would enable lectures and content produced in Kigali, where Kepler runs another campus, or elsewhere to be shared in real-time with Kiziba campus.

Considering there is a carrier in the region, it would be the most efficient, according to the proposed framework, to collaborate with Airtel and upgrade the service to provide a sufficient bandwidth to students. However, lack of power is one of the constraints in Kiziba camp, and the electric power infrastructure needs to be upgraded to support better communications infrastructure.

Since the camp's location is on a hill, the second option would be to establish a long-distance link to the fiber backbone connecting government offices in Rwanda, which is available in Kibuye, 15 km away. In this case, we would recommend establishing a WiLD connection to the Kibuye outpost.

6. Conclusions

The presented case studies are evaluated based on the proposed framework for choosing a telecom solution in the limited-resource settings. Table 1 presents a summary that relates those studies to the framework and Figures 1–3.

The proposed framework is based on a business approach for the implementations, even in low-resource settings. This approach requires having a business model in mind, with a value proposition and paying customers who may or may not be the users of the communication services. For the ICT interventions, the most important element of the business canvas are the key partners who will support sustainable growth of the community. If a local carrier is present in the community, the first choice would be cooperation with the carrier. If there is a local carrier but no high-speed internet is present, a private network is an option, but in such cases, it is important not to compete with the carrier because that would reduce the price of service and shrink revenue. The choice between WiLD and TVWS technologies, for the private network, will depend mostly on funding capabilities and the physical terrain.

Table 1. Summary of the case studies.

Case Study	Value Proposition	Key Partners	Telecom Solution
HPWREN	Transmit data from Mount Palomar to UCSD and provide data-intensive links to Indian reservations	Heterogeneous public-private partnership: some local carriers and some private networks	Build WiLD links where possible and lease service from commercial network where necessary
Rwandan Health project	Enable electronic collection of medical data by Rwandan Community Health Workers	Collaboration with the existing carrier	Purchase a discounted service from a local carrier (MTN)
NapoNet	Build communication infrastructure along Napo river without validated value proposition	There was no local carrier in the area because of the bad terrain	Build WiLDNet al.ong the river
Camacho Net	Provide broadband links between health posts in Bolivia	There is a local carrier but very expensive	Devise a private subscription network that does not compete with the present carrier
Papua New Guinea	Enable provision of educational courses to community members assuming that schools would pay for the dissemination	There is a local carrier providing 2G, but 3G service is very expensive	Consider WiLDNet for providing 3G service
University in Kiziba camp	Provide better internet access for the university students in the camp	There are several local carriers that offer cellular service in the area	Purchase service from a local carrier with an upgrade in the infrastructure

Author Contributions: A model for the decision framework was developed jointly by both authors during their extensive discussions. Suzana Brown was an investigator in the two case studies in Rwanda, hence in this paper she wrote about them. Alan Mickelson was an investigator in the other four of the presented case studies and he contributed with their description.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Viterbi, A.J.; Omura, J.K. *Principles of Digital Communication and Coding*; Courier Corporation: North Chelmsford, MA, USA, 2013.
2. Warschauer, M. *Technology and Social Inclusion: Rethinking the Digital Divide*; MIT Press: Cambridge, MA, USA, 2004.
3. Tapscott, D. *The Digital Economy: Promise and Peril in the Age of Networked Intelligence*; McGraw-Hill: New York, NY, USA, 1996; Volume 1.
4. Díaz Andrade, A.; Urquhart, C. The affordances of actor network theory in ICT for development research. *Inf. Technol. People* **2010**, *23*, 352–374. [CrossRef]
5. Amadei, B.; Sandekian, R.; Thomas, E. A model for sustainable humanitarian engineering projects. *Sustainability* **2009**, *1*, 1087–1105. [CrossRef]
6. Heeks, R. Do information and communication technologies (ICTs) contribute to development? *J. Int. Dev.* **2010**, *22*, 625–640. [CrossRef]
7. Breidlid, A. *Education, Indigenous Knowledges, and Development in the Global South: Contesting Knowledges for a Sustainable Future*; Routledge: London, UK, 2013; Volume 82.
8. Micholia, P.; Karaliopoulos, M.; Koutsopoulos, I.; Navarro, L.; Baig, R.; Boucas, D.; Michalis, M.; Antoniadis, P. Community Networks and Sustainability: A Survey of Perceptions, Practices, and Proposed Solutions. *arXiv*, **2017**, arXiv:1707.06898.

9. Ritter, C.; Mickelson, A.R.; Leventhal, J.; Espinoza, D. Presenting the Naponet: Developing global competencies through communications technology in the Peruvian amazon. In Proceedings of the American Society of Engineering Education (ASEE) Annual Meeting, Atlanta, GA, USA, 23–26 June 2013.
10. Sridhar, K.S.; Sridhar, V. Telecommunications infrastructure and economic growth: Evidence from developing countries. *Appl. Econom. Int. Dev.* **2007**, *7*, 2.
11. Oh, S.W.; Ma, Y.; Tao, M.H.; Peh, E.C.Y. An overview and comparison of TV white space regulations worldwide. In Proceedings of the International Conference on Frontiers of Communications, Networks and Applications (ICFCNA 2014—Malaysia), Kuala Lumpur, Malaysia, 3–5 November 2014.
12. Nandi, S.; Thota, S.; Nag, A.; Divyasukhananda, S.; Goswami, P.; Aravindakshan, A.; Rodriguez, R.; Mukherjee, B. Computing for rural empowerment: Enabled by last-mile telecommunications. *IEEE Commun. Mag.* **2016**, *54*, 102–109. [CrossRef]
13. Anand, A.; Pejovic, V.; Belding, E.M.; Johnson, D.L. VillageCell: Cost effective cellular connectivity in rural areas. In Proceedings of the Fifth International Conference on Information and Communication Technologies and Development, Atlanta, GA, USA, 12–15 March 2012; ACM: New York, NY, USA, 2012; pp. 180–189.
14. Mishra, S.M.; Hwang, J.; Filippini, D.; Moazzami, R.; Subramanian, L.; Du, T. Economic analysis of networking technologies for rural developing regions. *Lect. Notes Comput. Sci.* **2005**, *3828*, 184–194.
15. Cui, P.; Liu, H.; Rajan, D.; Camp, J. A measurement study of white spaces across diverse population densities. In Proceedings of the 2014 12th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), Hammamet, Tunisia, 12–16 May 2014; IEEE: Piscataway Township, NJ, USA, 2014; pp. 30–36.
16. Chiaraviglio, L.; Blefari-Melazzi, N.; Liu, W.; Gutierrez, J.A.; Van De Beek, J.; Birke, R.; Chen, L.; Idzikowski, F.; Kilper, D.; Monti, J.P.; et al. 5G in rural and low-income areas: Are we ready? In Proceedings of the ITU Kaleidoscope: ICTs for a Sustainable World (ITU WT), Bangkok, Thailand, 14–16 November 2016; IEEE: Piscataway Township, NJ, USA, 2017; pp. 1–8.
17. Gourhant, Y.; Lukashova, E.; Sama, M.R.; Wahed, S.A.; Meddour, D.E.; Venmani, D.P. Low-cost wireless network architecture for developing countries. In Proceedings of the 2014 14th International Conference on Innovations for Community Services (I4CS), Reims, France, 4–6 June 2014; IEEE: Piscataway Township, NJ, USA, 2014; pp. 16–21.
18. Mendez-Rangel, J.; Lozano-Garzon, C. A network design methodology proposal for e-health in rural areas of developing countries. In Proceedings of the 6th Euro American Conference on Telematics and Information Systems, Valencia, Spain, 23–25 May 2012; ACM: New York, NY, USA, 2012; pp. 339–345.
19. Reigadas, F.J.S.; Fernandez, A.M.; Garcia, P.O.; Sanz, S.L.F.; Pascual, J.S. The design of a wireless solar-powered router for rural environments isolated from health facilities. *IEEE Wirel. Commun.* **2008**, *15*. [CrossRef]
20. Zakrzewska, A.; D'Andreagiovanni, F.; Ruepp, S.; Berger, M.S. Biobjective optimization of radio access technology selection and resource allocation in heterogeneous wireless networks. In Proceedings of the 2013 11th International Symposium on Modeling & Optimization in Mobile, Ad Hoc & Wireless Networks (WiOpt), Tsukuba Science City, Japan, 13–17 May 2013; IEEE: Piscataway Township, NJ, USA, 2013; pp. 652–658.
21. DeMaagd, K. The Myth of Population Density and ICT Infrastructure. In Proceedings of the 42nd Hawaii International Conference on System Sciences, HICSS'09, Big Island, HI, USA, 5–8 January 2009; IEEE: Piscataway Township, NJ, USA, 2009; pp. 1–10. [CrossRef]
22. Nielsen, C.; Lund, M. *Business Models*; Bookboon: London, UK, 2013.
23. Osterwalder, A.; Pigneur, Y. Aligning profit and purpose through business model innovation. In *Responsible Management Practices for the 21st Century*; Pearson: London, UK, 2011; pp. 61–75.
24. Blank, S. *The Startup Owner's Manual: The Step-by-Step Guide for Building a Great Company*; BookBaby: Pennsauken, NJ, USA, 2012.
25. Koen, P. Lean Startup in Large Enterprises Using Human-Centered Design Thinking: A New Approach for Developing Transformational and Disruptive Innovations. Howe School Research Paper No. 2015-46. Available online: https://ssrn.com/abstract=2566916orhttp://dx.doi.org/10.2139/ssrn.2556187 (accessed on 27 January 2015).
26. Wessner, D. Inverted humanitarian service and learning: The CSI Haitian pilot examined in doodles and parables. In Proceedings of the Global Humanitarian Technology Conference (GHTC), San Jose, CA, USA, 20–23 October 2013; IEEE: Piscataway Township, NJ, USA, 2014; pp. 300–303.

27. Bwalya, K.J.; Du Plessis, T.; Rensleigh, C. Multi-Dimensional Factors Impacting on E-Government Adoption in Botswana, Mozambique, and Malawi. In *Adoption of Virtual Technologies for Business, Educational, and Governmental Advancements*; IGI Global: Hershey, PA, USA, 2013; pp. 58–71.
28. Patra, R.K.; Nedevschi, S.; Surana, S.; Sheth, A.; Subramanian, L.; Brewer, E.A. WiLDNet: Design and Implementation of High Performance WiFi Based Long Distance Networks. In Proceedings of the 4th USENIX Symposium on Networked Systems Design & Implementation (NSDI '07), Cambridge, MA, USA, 11–13 April 2007.
29. Espinoza, D.; Mickelson, A.; Leventhal, J.; Ritter, C.; Quispe, R.; Linan, L. A VoIP enabled cooperative network for agricultural commerce in amazon Peru. In Proceedings of the 2013 IEEE Global Humanitarian Technology Conference, San Jose, CA, USA, 20–23 October 2013; pp. 343–348.
30. O'Flynn, B.; Regan, F.; Lawlor, A.; Wallace, J.; Torres, J.; O'Mathuna, C. Experiences and recommendations in deploying a real-time, water quality monitoring system. *Meas. Sci. Technol.* **2010**, *21*, 124004. [CrossRef]
31. Zennaro, M. Wireless Sensor Networks for Development: Potentials and Open Issues. Ph.D. Thesis, KTH, School of Information and Communication Technology (ICT), Quezon City, Philippines, 2010.
32. Zennaro, M.; Bagula, A.; Nkoloma, M. From training to projects: Wireless sensor networks in Africa. In Proceedings of the Global Humanitarian Technology Conference (GHTC), Seattle, WA, USA, 21–24 October 2012; pp. 417–422.
33. Thapa, D.; Saebo, O. Demystifying the possibilities of ict4d in the mountain regions of Nepal. In Proceedings of the 44th Hawaii International Conference on Systems Sciences, Kauai, HI, USA, 4–7 January 2011; pp. 1–10.
34. Saebo, O.; Sein, M.K.; Thapa, D. Nepal wireless networking project: Building infrastructure in the mountains from ground up. *Commun. Assoc. Inf. Syst.* **2014**, *34*, 242–256.
35. Surana, S.; Patra, R.; Nedevschi, S.; Brewer, E. Deploying a rural wireless telemedicine system: Experiences in sustainability. *Computer* **2008**, *41*, 48–56. [CrossRef]
36. Sandvig, C. Connection at Ewiiaapaayp Mountain: Indigenous Internet infrastructure. In *Race after the Internet*; Nakamura, L., Chow-White, P., Eds.; Routledge: New York, NY, USA, 2011; pp. 168–200.
37. Physicians per 100,000 People, by Country. Available online: http://www.infoplease.com/ipa/A0934558.html (accessed on 22 October 2017).
38. Condo, J.; Mugeni, C.; Naughton, B.; Hall, K.; Tuazon, M.A.; Omwega, A.; Nwaigwe, F.; Drobac, P.; Hyder, Z.; Ngabo, F.; et al. Rwanda's evolving community health worker system: A qualitative assessment of client and provider perspectives. *Hum. Resour. Health* **2014**, *12*, 71. [CrossRef] [PubMed]
39. Brown, S.; McSharry, P. Improving accuracy and usability of growth charts: Case study of Rwanda. *Br. Med. J.* **2016**, *6*, e009046. [CrossRef] [PubMed]
40. "Rwanda Economic Outlook", African Development Bank, African Economic Outlook 2015. Available online: http://www.afdb.org/en/countries/east-africa/rwanda/rwanda-economic-outlook/ (accessed on 22 October 2017).
41. Haslett, C. *Essentials of Radio Wave Propagation*; Cambridge University Press: London, UK, 2008; pp. 119–120, ISBN 978-0521875653.