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CONNECTING THE UNCONNECTED –

TACKLING THE CHALLENGE OF COST-EFFECTIVE BROADBAND INTERNET IN RURAL AREAS

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Executive Summary

Global Internet penetration has increased significantly over the last decades, surpassing 50% of the world's population as widely announced at the end of 2017. This, however, also means that the other half of the world's population is still unconnected.

Typical barriers to Internet adoption include lack in Ability, Appetite as well as Access and its Affordability. In other words, despite an overall increase in coverage and ever faster technologies, the slow, unreliable or often non-existent Internet connection along with often prohibitively high usage costs, lead to about 2.5 billion people that live within the reach of a broadband network but are still not using the Internet.

Especially in rural areas, high costs of providing connectivity are a major obstacle as they are met by an extremely low income potential for operators. The reasons for this are manifold and range from lack of infrastructure and skilled personnel over insufficiently regulated markets and inflexible business models to funding challenges.

The need to act has been recognized by industry and governments. The global community reflected the need in one of the 17 Sustainable Development Goals (SDGs) 9c: "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". However, it is widely recognized that current approaches are not sufficient to reach this goal.

A number of industry initiatives have appeared in recent years to address the challenge of rural connectivity. Well-known examples are the balloons of Google Loon, Facebook's Aquila Drone, Low Orbit Satellites or the efforts to provide *free* implementations of cellular network technologies. These initiatives promise to allow extending the business of mobile operators and may provide the basis for entirely new actors and business models to help bridge the digital divide. However, most of such novel solutions have yet to prove their viability and applicability in general or in the context of developing countries, in particular. Often such technologies are not yet technically mature, face regulatory challenges or significant royalty fees.

Numerous projects worldwide have been experimenting with such alternative concepts. Some are in active pilot or even commercial operation. Therefore valuable information can be gathered from those and is presented here in the form of Best Practice or Lessons learned recommendations. These include technological alternatives for established telecom operators as well as completely new actors alike. Additionally, new operator models, enabled by such alternative technologies that include and are based on the local communities provide new options and new definitions of "profit" - where sustainable and affordable Access is the profit for communities instead of the financial Return of Investment (ROI).

This White Paper examines such new developments and evaluates the potentials of both novel and mature technologies in the context of rural areas of the developing world. Its main focus is to discuss different technological solutions to connect people and instruments that have so far proven their practicability. To this end, it identifies and assesses challenges and potentials for prospective stakeholders such as development cooperation actors and private donors in the application of such novel approaches and highlights possible fields of action such as regulation, piloting, scale-up, and skill development.

Connecting villages and regions (Backhaul) as well as providing access to the people (Last Mile) have been identified as key areas where this White Paper discusses different technical and regulatory aspects which contribute to sustainable solutions to connect the unconnected.

1 Introduction

Global Internet penetration has increased significantly over the last decades, surpassing 50% of the world's population as widely announced at the end of 2017. However, this also means that the other half of the world's population is still left out of the undisputed potentials of digitalization. Not being able to profit from its advantages means falling behind even further compared to those that are connected – a **"Digital Divide"** has formed.

The **barriers to Internet adoption** include the lack of ICT-Skills (**Ability**) and relevant online content as well as the missing population's awareness of valuable services (**Appetite**). Furthermore, despite an increase in overall network coverage and ever faster technologies, the slow, unreliable, or completely missing **Access** to a communication infrastructure along with often prohibitively high usage costs (**Affordability**) remains a significant hurdle. To briefly illustrate the Access and Affordability gap: 1.2 billion people still live outside the reach of broadband networks (3G or higher), and about 400 million live outside of the reach of any network at all. Even within the reach of a network, its performance and reliability might, especially in rural areas, be insufficient and the available Access may not be affordable at local income levels. Users in developing countries have to spend 11-25% of their monthly income on connectivity while in industrialized countries this is just 1-2%.[1] As a consequence, about 2.5 billion people live within the reach of a broadband network but are not connected.[2]

Especially rural areas, where roughly 60% of the world's offline population resides,[3] **are affected**. In these areas high costs of providing connectivity are a major obstacle as they are met by an extremely low income potential for operators. The cost factors for network deployment and operation include a lack of infrastructure such as energy grids, a shortage of skilled personnel, as well as the long distances to cover sparsely populated areas. Political instability, insufficiently regulated markets or lack of funds are also considerable hurdles. In consequence, the **economically sustainable** deployment and operation of networks remains a significant challenge, which the market has yet not been able to solve; instead, operators focus on the profitable urban areas.

The **need to act** has been recognized by industry and governments. The global community reflected the need in one of the 17 SDGs 9c: "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". The International Telecoms Unions (ITU) aims to bring 60% of the world online by 2020 in its Connect 2020 Agenda. Furthermore, with the "1 for 2 target" a prominent affordability goal has been set. The target of 1 GByte of mobile broadband costing 2% or less of the average monthly income has recently been endorsed by the United Nations (UN) Broadband Commission. At the same time, connecting the unconnected appears to be an increasingly challenging and time-consuming task. Not only the GSM Association (GSMA), an association representing nearly 800 mobile operators, predicts a slowing pace in the expansion of mobile networks [4]; the Alliance for Affordable Internet expects that, with today's methods and options, the SDG 9c will be missed by 20 years.[5] Also the ITU projects that only few Internet users will be added in rural areas within the next years and expects their connectivity target to be missed.

The need for new solutions and approaches is therefore eminent and a number of industry ini-

[1] Phillipa Biggs et al. *The State of Broadband 2016: Broadband Catalyzing Sustainable Develop ment*. 2016.

[2] GSMA Intelligence. "Global Mobile Trends 2017". In: *GSMA, September* (2017).

[3] I Philbeck. "Connecting the Unconnected: Working Together to Achieve Connect 2020 Agenda Targets". In: *A background paper to the special session of the Broadband Commission and the World Economic Forum at Davos Annual Meeting*. 2017.

[4] GSMA - 2017 Global Mobile Trends Report

[5] A4AI Alliance for Aforadable Internet. *Affordability Report*. 2017. url: `http://a4ai.org/affordability-report/` (visited on 01/07/2018).

tiatives, such as the Telecom Infra Project (TIP)[6] have appeared in recent years, addressing these challenges in very innovative ways. Well-known examples are the balloons of Google Loon, Facebook's Aquila drone, low orbit satellites, or the efforts to provide *free* implementations of cellular network technologies. These initiatives and their developments promise to allow extending the business of mobile operators into rural areas at a higher pace. They also provide the basis for entirely new actors and business models, promising, e.g. in case of the low orbit satellite initiative OneWeb, to completely bridge the access Digital Divide within a decade.[7] However, the real potential of these initiatives and technologies has yet to be seen. Most have yet to prove their viability and applicability in general or in the context of developing countries, in particular. Often such technologies are not yet technically mature, face regulatory challenges or royalty burdens.

This White Paper takes a closer look at such new developments and qualitatively evaluates the potentials of both novel and mature technologies as well as emerging business concepts applicable to rural areas of the developing world. Furthermore, this White Paper identifies challenges that hinder their application today and outlines fields of activities for governments and prospective stakeholders to promote the adoption of these approaches. We also briefly discuss overall funding aspects, but refer the interested reader to more in-depth studies, such as[8].[9]

2 Overview of Technologies

Primer: *Telecommunication networks can roughly be divided into three segments. As can be observed in almost all fields of logistics, the transport of people and goods takes place in different scales and dimensions. Thus – by analogy – the extension of urban communication Infrastructures into rural areas can be compared with public transport:*

The first segment comprises long-distance flight or train connections. Airports and railway stations are usually located in densely populated cities and accommodate high volumes of passengers. This corresponds to the high data rates in nation-wide fiber networks, the so-called ***Backbone****.*

The second segment transports passengers from destination airports and stations beyond the city limits into rural areas. Bus and tram stops are linked at regular intervals. In telecommunication networks, the stations that connect remote locations outside the main network constitute the ***Backhaul*** *segment.*

The third segment describes the last stretch from the bus or tram stop to the passengers' doorstep. Local residents use these centralized collecting points to enter and exit public transport. This is comparable to the point from which telecommunication services are brought to the customers' nearby homes, also known as ***Last Mile****.*

The more densely populated the area, the more demanding the infrastructure. But also the more paying customers and the more favorable technical and economically feasible solutions exist. Ubiquitous Broadband network coverage will only be provided if operating such networks generates a certain "return" - financially or socio-economically. While public transport operates low-capacity vehicles at longer intervals as the population density decreases, communication networks for rural low-income areas still lack similarly scalable business models and cost-effective but reliable technologies.

[6] *Telecom Infra Project*. 2018. url: `https://www.telecominfraproject.com` (visited on 01/08/2018).

[7] *OneWeb*. 2018. url: `http://www.oneweb.world/` (visited on 01/08/2018).

[8] intelcom research & consultancy ltd. *A Desktop Study on Broadband Infrastructure in Africa: Investment Needs and Potential Role of KfW Development Bank*. Tech. rep. 2016.

[9] D. Thakur and Potter L. *Universal Service and Access Funds: An Untapped Resource to Close the Gender Digital Divide*. Tech. rep. Washington DC: Web Foundation, 2018.

Economically feasible solutions for Broadband Internet access in rural areas, where circumstances such as low population density and very low income prevail, require novel approaches to address these challenges. A variety of possible solutions has been discussed in recent years. This section provides an overview of current technologies in such low-income scenarios and analyzes their specific strengths and weaknesses as well as their potential to help pushing the boundaries for sustainable operation in rural areas.

The definition of what 'Broadband' means in terms of perceived quality is being shifted constantly towards ever higher data rates. While it is possible in some areas to subscribe to gigabit-to-the-home, the common definition of 'Broadband' **ranges from about 1 Mbit/s over 30 MBit/s (i.e. EU goal) to greater than 100 Mit/s**. Here it is important to note that, a typical Internet user does not constantly require those data rates. There are peaks when, for example, a web site is downloaded, and there are longer idle times when the content is viewed. Such data rates are therefore not necessarily required 24/7, but the user should be provided accordingly when accessing the Internet [10]. This aspect is typically referred to as 'Overbooking' and typical factors range from 5 to 30 or more. **In the context of this White paper (rural areas) we assume a minimum of 1 Mbit/s per user and an overbooking factor of about 20 while pointing out that also those minimum requirements will be constantly increasing in order to not cut off rural areas (again) from the ever growing Internet.**

In order to provide a comparison of the various technologies, we first introduce common characteristics, general limitations and design trade-offs in the field of communication technologies.

Similar to electric power grids, communication networks can be categorized into distinct segments from long distance bulk transport over distribution to end-user provisioning (see Figure 2.1):

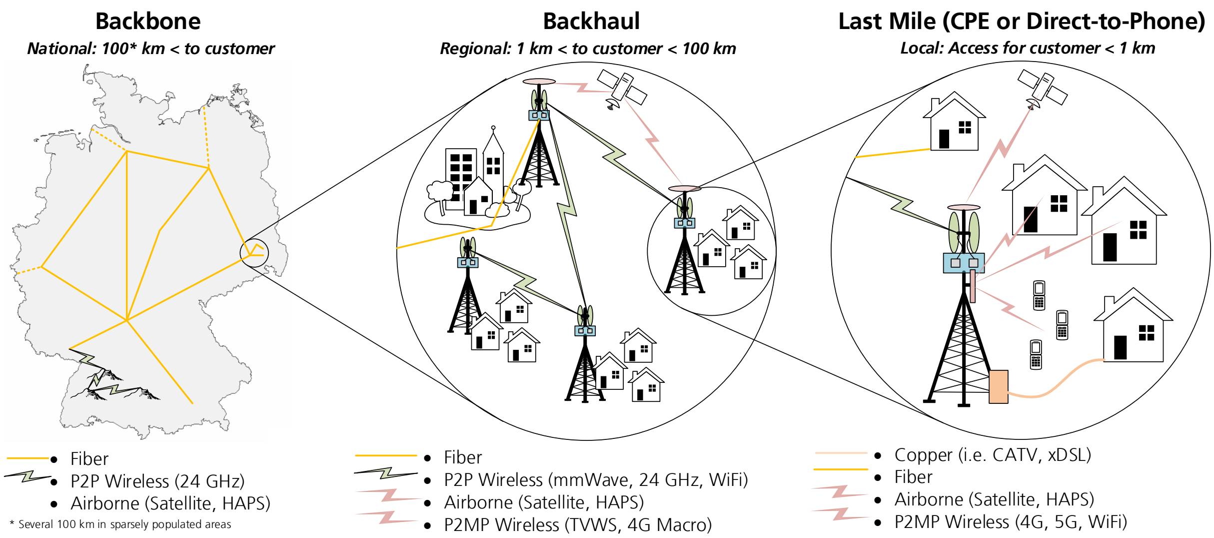

Figure 2.1: Three distinct network segments.

- **Backbone** — National Backbone Networks (high speed, redundant)
- **Backhaul** — Distribution Networks connecting Points of Presence to the Backbone
- **Last Mile** — Access Networks connecting homes. Typically, Customer Premises Equipments (CPEs) are assumed for in-door coverage (laptops or smartphones).

[10] This assumption does not hold true anymore for i.e. HD-video streaming, where data is constantly transmitted

These distinct segments differ in requirements and features. Depending on the deployed technology, terrain or user density, their ranges may vary significantly and may even overlap.

Regarding the Last Mile, it is important to note that the prevailing User Equipment (UE) in rural ares of developing countries is a smart phone (or older 2G mobile phone). Therefore, no CPE such as a DSL router or Wireless Fidelity (WiFi) Access point is present in such homes. Hence, when considering a Last Mile technology in this White Paper, we point out if an additional CPE is required for (in-door) coverage as this may be a major cost factor. Furthermore, an additional CPE increases the dependency on access to stable electricity.

Stable, redundant Backbone networks are crucial for the overall communication infrastructure and there are many initiatives (financially) supporting the build-up of such Backbones using well-established and readily available components. While limited Backbone deployments and the cost of capacity for such networks are often the key bottlenecks for sustainable connectivity in rural areas, there are no (longer-term) technological alternatives to either Fiber or, in some cases, MicroWave links (see technology specific sections below). Hence, this White paper focuses on the Backhaul and Last Mile segments, which play the major role in connecting the unconnected. **Fair sharing at reasonable cost of Backbones is a key requirement** to enable such rural connectivity initiatives which is mainly a regulatory or political issue.

As a general rule of thumb for all communication technologies, all other parameters being equal, **the greater the distance between two points, the smaller the amount of information they will be able to exchange per unit of time. Also, the higher the frequency, the shorter the effective range (or cell size)**. In the Wireless domain, this often leads to a trade-off between capacity and overall costs as longer range connections require less infrastructure on the ground. In wireless Last Mile segments, lower frequencies are preferable due to their capability to provide in-door coverage even at longer distances, but the available spectra at these frequencies may be limited (see TV White Space (TVWS) section) and also Figure 2.2.

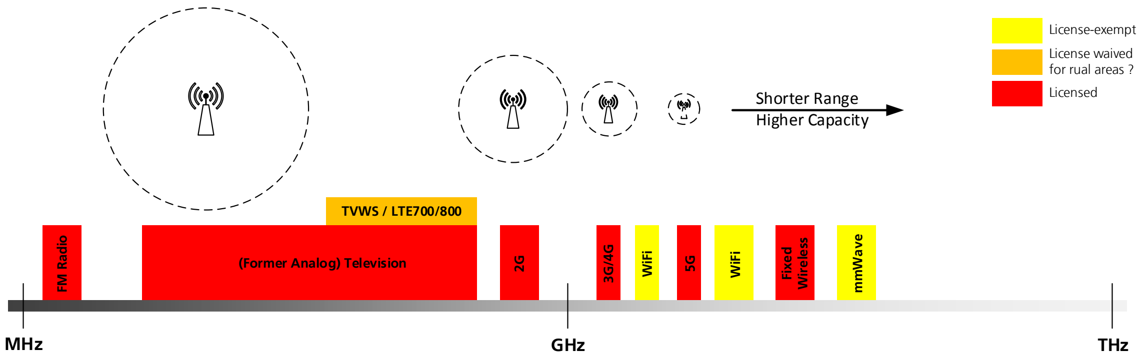

Figure 2.2: Simplified frequency spectrum with typical bands and resulting cell sizes.

The respective network architecture, especially the mix of Point To Point (P2P) or Point To Multipoint (P2MP) technologies, has a major impact on costs as well as the per-user capacity. In general, **P2P architectures provide higher capacity but require more equipment to be installed**, while **P2MP architectures imply lower per-user costs but also lower capacity since multiple users share the medium** (air or cable). If network planning and design is not done carefully, during the peak hours of the day, bandwidth sharing in P2MP architectures often leads to bottlenecks which may deteriorate the service quality significantly. On the other hand, very large P2MP cells can connect a larger number of users with lower bandwidth-services (voice or messenger services only). **Hence proper network dimensioning and the right mix of technologies matching**

the actual or projected demand is essential and a properly defined regulatory framework should be in place to ensure proper per-user capacity.

The remainder of this section follows a top-down approach from common to innovative solutions. Each technology is summarized with common criteria for each possible network segment. Among these criteria, Technology Readiness Level (TRL) and Quality of Experience (QoE) are used as compound indicators to describe the maturity of a technology (for the rural areas use case) as well as the expected user experience when accessing the Internet over the respective technology. Optionally, we list possible alternative or supplemental technologies. The Costs include Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) on a per-user basis and allow for a relative ranking among the suitable technologies for each network segment.

2.1 Digital Subscriber Line (DSL) and Cable Television (CATV)

Using copper wires (telephone) or coaxial cables (TV broadcasting) is by far the most common broadband access technology in countries where such infrastructure is already deployed. If either one of these cables infrastructures exists, re-using it (in the mid-term) as a Last Mile technology seems reasonable. Although it should be noted that, in developing countries, cable-based Last Mile systems are typically not available outside major urban areas.

For areas where cable-based provisioning has not yet begun, investments in copper or coaxial wires should not be considered; instead, fiber, or (in very rural areas) fiber-like wireless technologies should be deployed.

Copper wires are intertwined with DSL technologies where the main challenge is the signal attenuation preventing high capacity at longer distances (about >2km). CATV is a P2MP technology where the users share the capacity of the cable. For both technologies, the goal is to keep the maximum cable length to the next high speed peering point (e.g. DSLAM) within acceptable bounds by investing in the Backbone and/or Backhaul (e.g. Fiber-To-The-Curb (FTTC)).

Segment	Favored	QoE	Costs	Supplement	TRL	Remarks
Backhaul	✗	−−	\$-\$\$	Fiber	++	
Last Mile	✓	+	\$		++	CPE, Consider only if present

Table 2.1: xDSL and CATV

2.2 Fiber

Optical fiber networks allow symmetric transmission rates of up to hundreds of GBit/s even on long distances. **The deployment of fiber as close to the customer as possible is the best solution for a future-proof network and alternatives should only be considered where a pure fiber solution (Backbone, Backhaul and Last Mile) is not economically feasible.** However, due to a challenging topography, a low population density and (very) low-income subscribers in rural areas, the initial CAPEX often cannot be recovered within reasonable time, especially in rural areas of developing countries.

The costs for the optical fiber itself is relatively low. The main cost driver in rural areas are the required civil engineering (up to 90%) and scarce qualified staff for splicing the interconnections. To minimize digging, common approaches are the use of existing structures such as electricity poles (aerial fiber) or the mandatory installation of a conduit for fiber-optic cable during road construction

(DigOnce) [11]. Another approach to reducing civil engineering costs, particularly for the Last Mile, is called Micro-Trenching, where a narrow, shallow trench is typically cut in asphalt. Techniques such as pushable fiber have emerged to simplify the installation (splicing), especially on the Last Mile. Inadequate access to Rights of Way (ROW) can be a major issue that can have a major impact on costs and deployment times.

Segment	Favored	QoE	Costs	Supplement	TRL	Remarks
Backbone	✓	++	$$-$$$	(MiroWave)	++	Mandatory mid-term
Backhaul	✓	++	$$-$$$	Directional Wireless	++	Mandatory long-term
Last Mile	✓	++	$$$	Copper, Cellular, WiFi Mesh	++	CPE, Often too costly

Table 2.2: Fiber

Despite other emerging Backhaul solutions (Directional Wireless, Satellites, Airborne), **the deployment of fiber in the Backbone and also the Backhaul should be considered mandatory in both the medium and long-term**.

2.3 Cellular / Mobile Networks (2G/3G/4G/5G)

Cellular or mobile networks are characterized by a P2MP architecture where each cell is served by one base station. To be effective, base stations require an exposed location and the availability of a stable electricity as well as a high-speed interconnection to the Backbone. Mobile networks are designed as Last Mile networks. However, for rural areas with a sparse population density, macro-cells of up to 30km range or self-backhauling are used to avoid the need for a Backhaul infrastructure. However, the expected capacity per user at such distances (fringe of network) is minimal — significantly below 1 Mbps. Furthermore, in rural areas with limited access to grid power, to charge the devices, the trade-off between range, capacity, and power-consumption needs to be considered.

5G is currently one of the most discussed topics and the first commercial roll-outs are expected soon. However, while 5G promises a radical increase in peak rates, current research and standardization efforts are focused on high density urban scenarios.[12] The main innovations for 5G are the usage of higher frequency bands, which leads to a decreased cell size and various optimizations (e.g. Massive MIMO), allowing for an increased per-user capacity.

To date, the CAPEX and OPEX of cellular networks is significant and often prohibitive for a sustainable deployment in low-income areas. While the costs for UEs are very low, the costs for the infrastructure (e.g. Base Stations, tower, electricity, cooling) are very high. Also, most countries auction the required frequency for billions of dollars which the operator then has to recover from its customers.

Cellular networks are not a standalone solution to reach out into rural areas as cellular base stations require connectivity to the Backbone. However, with the ever-increasing penetration of smartphones and initiatives to reduce the costs of base station with open-source soft- and hardware (e.g. OpenBTS,[13] OpenCellular,[14] OpenAirInterface[15] or NextEPC[16]), cellular networks have the poten-

[11] An approach promoted by the US-lead Global Connect Initiative to help bridge the digital divide

[12] Mats Eriksson and Jaap van de Beek. *IS ANYONE OUT THERE? 5G, RURAL COVERAGE AND THE NEXT 1 BILLION*. 2015. url: `https://www.comsoc.org/ctn/anyone-out-there-5g-rural-coverage-and-next-1-billion`.

[13] *OpenBTS*. 2018. url: `http://openbts.org/`.

[14] *Telecom Infra Project*.

[15] *OpenAirInterface*. 2018. url: `https://www.openairinterface.org`.

[16] *NextEPC*. 2018. url: `http://nextepc.org`.

tial to serve as the major Last Mile solution for universal affordable access in rural areas. A major issue regarding OpenSource/OpenHardware approaches is that 3G/4G/5G technologies are heavily patented. Only for early Global System for Mobile Communications (GSM) standards (2G/2.5G), this patent protection has expired. **An arrangement with the Intellectual Property Right (IPR) holders to waive royalty fees in very low-income areas together with a free-of cost spectrum licensing scheme would make this technology a good fit for many rural scenarios, particularly in lower sub-GHz frequency bands such as 700 MHz or 800 MHz, where also in-door coverage can be accomplished (see also the TVWS section).**

For example, Germany has freed up the sub-GHz TV spectrum (digital dividend) and auctioned it as alternative frequency bands to mobile Internet Service Providers (ISPs). Here, Long Term Evolution (LTE) is deployed in the 800 MHz spectrum to span larger cells covering rural areas (LTE700 is following in 2019/2020). The rationale of this approach in rural areas is that most modern smart phones already support LTE800 and support for LTE700 is imminent. Hence, no extra costs on the UE side are incurred for the user. If more bandwidth is required, there are cost-effective CPEs with outdoor antennas to improve the signal reception. **Instead of auctioning the spectrum, it could be assigned free-of-costs to operators in low-income areas or to municipalities which could then contract an operator to provide broadband Internet access.**

Segment	Favored	QoE	Costs	Supplement	TRL	Remarks
Backhaul	✗	–	$$-$$$	Directional Wireless, Fiber	++	Macrocell
Last Mile	✓	+	$$	WiFi Mesh/HotSpot	++	Smallcell

Table 2.3: Cellular / Mobile Networks (4G/5G)

2.4 Satellites

Satellite networks are typically characterized by a P2MP architecture where large cells are provided from the sky, eliminating the need for a terrestrial Backbone or Backhaul infrastructures. A Last Mile technology is required to connect the UE.

Difficult to reach areas can therefore easily be connected via satellites. However, given the extremely large cell sizes, the capacity per user is currently rather limited. As a complementary solution, satellite networks can speed up slower terrestrial infrastructures (Backhaul).[17]

The main advantage of satellite-based systems is the coverage and their reach into very remote rural areas without the need for a terrestrial infrastructure (Backbone and Backhaul).

Satellite connectivity (OPEX) is very expensive, and in most cases, in the longer term, building one's own Backbone using wireless to the closest fiber is more cost-efficient.

2.4.1 GEO

Geosynchronous Earth Orbit (GEO) satellite systems have been in use for decades and are regaining attention with the idea of using higher frequencies (Ka-band) and multiple but relatively small spot beams to achieve aggregate capacities exceeding 1 Terabit/s. The main issues with GEO satellite communication is the typical round trip time for a message of more than 500 ms seconds which

[17] J Pérez-Trufero et al. "Broadband Access via integrated Terrestrial and Satellite systems (BATS)". in: *Ka and Broadband Communications, Navigation and Earth Observation Conference*. 2013.

renders them less suitable for voice or real-time data and even web surfing feels sluggish. **Therefore, GEO satellites offer a solution of last resort, but should not be invested into as a longer-term solution for Internet access in rural areas.**

Segment	Favored	QoE	Costs	Supplement	TRL	Remarks
Backbone & Backhaul	✗	−−	\$\$-\$\$\$	Cellular, Directional Wireless	++	
Last Mile	✗	−−	\$\$		++	CPE

Table 2.4: GEO Satellites

2.4.2 MEO and LEO

Medium Earth Orbit or Low Earth Orbit systems operate in lower orbit (between 160 km and 2000 km), compared to about 35700 km for GEO satellites, which significantly reduces the round trip time (10...100ms). In addition, inter-satellite communication is proposed to reduce the number of times the signal needs to travel to the earth and back.

Medium Earth Orbit (MEO) or Low Earth Orbit (LEO) actors such as OneWeb (and similarly also SpaceX or O3b) claim to be closing the *digital divide* by 2027 by launching constellations of numerous satellites that could provide continuous Internet service to almost all areas of the earth. For example, OneWeb aims to launch over 600 LEO satellites with a beam-width of 1 Million km^2 (roughly the size of Germany) at 7.5 Gbps per satellite.

Can a LEO-based solution ultimately provide sufficient per-capacity for the under-served population (1.2 billion) rendering investments in fiber deployments irrelevant? Considering the proposed beam-width and capacity per satellite of the OneWeb project in relation to the population density in Sub-Saharan Africa and applying a generous overbooking factor of 200 leads to a capacity per user significantly lower than that of a legacy modem (56k)[18]. In addition, the handover of ground stations, inter-satellite communication as well as signaling to the ground at high speeds while maintaining a high throughput pose considerable challenges. As there are no existing examples in the real world, the business cases of such deployments should be duly scrutinized.

Other factors such as the market-dominating power of single satellite ISPs and the fact that the lower earth orbit already faces the challenge of an increasing amount of space debris should also be kept in mind.

Segment	Favored	QoE	Costs	Supplement	TRL	Remarks
Backbone & Backhaul	✗	−−	\$\$-\$\$\$	Cellular, Directional Wireless	−−	
Last Mile	✗	−	\$\$		−−	CPE or special UE

Table 2.5: MEO or LEO Satellites

[18] Approximation: Rural population of Sub-Saharan Africa 650 million people, data source is the World Bank. Land-Area of Sub-Saharan Africa 25 Million km^2, data source is the World Bank. Therefore, population density of 26 people per km^2. Beam-width per satellite 1 Million km^2, data source is the OneWeb technical narrative for the FCC. Capacity per satellite 7.2 Gbps, data source is the OneWeb website. Overbooking-factor 200, very generous and about a magnitude higher compared to modern cellular networks.

$$\frac{7.2\ Gbps}{26\ \frac{people}{km^2} * 1\ Mio\ km^2} * 200 = 55.4 \text{ kbs per person} \quad (2.1)$$

2.5 Airborne (Drones, Balloons)

Other emerging ideas to distribute connectivity from the sky are summarized under the term High-Altitude Platforms (HAPs) or Airborne. Similar to mobile networks, a HAP creates a cell (P2MP architecture). Compared to LEO satellite-based solutions, the altitude is much lower (20 km) and the cell size is therefore smaller ($5000\ km^2$). HAPs can be classified into aerostatic (balloons, e.g. Google Loon) and aerodynamic (drones, e.g. Facebook). The former make use of buoyancy to float in the air, whereas the latter use dynamic forces created by movement.

HAPs are being developed by global Over-The-Top (OTT) players aiming to attract the untapped market mainly in developing countries, possibly by-passing the local terrestrial telecom providers. Viable technical information or even scientific publications addressing these solutions are rare, while media coverage is immense. To completely cover the area of Sub-Saharan Africa, more than 5000 HAPs would be needed assuming that HAPs could permanently maintain their current position. However, balloons are prone to dynamic drag while in the air and therefore even more balloons are needed for continuous Internet provisioning. Furthermore, the size of the balloons (about 15m in diameter) is challenging during take-off and landing.

To maintain a quasi-stationary position, drones need to circle above the coverage area which requires energy. Compared to LEO systems, HAP solutions also cover the Last Mile, potentially including in-door, allowing users to directly connect with their UE which reduces the costs. However, from a capacity point of view, each HAP spans a very large macro-cell which implies the same disadvantages that have been discussed for mobile networks. In addition, due to the altitude of few to many kilometers, the efficiency of the communication with the UE may often be sub-optimal (towards fringe of the cell). Similar to Cellular Networks, HAPs would benefit from sub-GHz spectrum to provide proper in-door coverage.

HAPs can be used to provide or complement terrestrial Backhaul and Last Mile infrastructures in areas most difficult to reach.

An important regulatory or legal aspect are overflight rights for HAPs as they operate in a country's air space.

Segment	Favored	QoE	Costs	Supplement	TRL	Remarks
Backhaul & Last Mile	✗	±	\$-\$\$		−−	

Table 2.6: Airborne (Drones, Balloons)

2.6 TV White Spaces

The term *White Space* refers to frequencies typically allocated to TV broadcasting services which are not or no longer in use at certain locations. Due to rather static nation-wide or even continent-wide spectrum allocations, most of such frequencies are unused, especially in rural areas of the developing world.

Although many of those frequencies are not being used, typical regulatory regimes prohibit their use for alternative purposes such as *rural broadband*, where the lower frequencies have substantial potential for deployments over longer distances in None Line of Sight (NLOS) situations and in-door coverage.

The main issues regarding the use of the unused *White Spaces* seem to be related to regulatory aspects and give rise to the following questions: Who should have the right to use which and how much spectrum at what costs? How to address fair sharing of such spectrum? How to avoid another static regime that unnecessarily blocks the use of those frequencies in rural areas? (See also the section on Cellular networks)

Dynamic spectrum technologies referred to as TVWS have emerged and have been tested in various countries. The main idea here is to look up in a (nation-wide) database if a certain frequency is not being used by its primary license holder (e.g. TV broadcaster) in a certain local and its wider vicinity. If so, it is utilized by the TVWS equipment for data transmission. TVWS equipment must abandon the frequency if it receives instructions from the database or if it detects a signal from the primary spectrum license holder.

The lack of use of TV frequencies in rural areas by the primary users allows for several tens of MHz to be aggregated for data transmission via P2MP macro cells. All other parameters being equal, this technology yields an attenuation due to vegetation which is 4 to 16 times less compared to WiFi-based Backhauling. Likewise, the transmission at these frequencies allows for up to about 10 km longer ranges. Altogether, this technology can provide a cost-effective solution to backhaul data traffic in hard-to-reach areas.

The use of TVWS is being limited beyond pilots proving the feasibility of the technology. With the approval of the regulation on the use of this technology in countries such as Colombia, South Africa, and Mozambique in the last year, an increase in commercial deployments is expected. This in turn should contribute to an increased availability of low-cost mass-market TVWS equipment.

Segment	Favored	QoE	Costs	Supplement	TRL	Remarks
Backhaul	✗	–	$	Directional Wireless, Fiber	–	CPE, Macrocell

Table 2.7: TVWS

2.7 Directional Wireless (Licensed and License-exempt)

Directional wireless links typically operate in P2P mode and are mainly used as a cost-effective wire-like alternative in the Backhaul segment to connect Last Mile technologies to the Backbone within ranges up to about 40km. Sometimes, directional wireless links may also be used to form so-called *MicroWave Backbones*.[19] In fact, mobile base stations are often provisioned via P2P wireless links. Using switches or routers, such P2P links can be concatenated (multi-hop) to reach longer distances or to even form more complex topologies such as rings to provide redundancy, fail-over, and load-balancing options. Depending on the used frequency band, directional wireless links can offer rates up to several Gigabit/s.

A key requirement for this approach is a given line-of-sight between the connected locations. Due to the curvature of the earth, tall(er) towers or high buildings are needed for long distance links. For example, a 10 km link requires a 10 m tower, while a 40 km link already requires a tower of 65m in height. In addition, each location requires electricity which can be challenging for forwarding or repeater nodes away from the main point of interest. There are different frequency bands that are typically used for directional wireless networks such as 5 GHz (i.e WiFi), 24 GHz (MicroWave) or 60 GHz (Millimeter Wave (mmWave)) and, often depending on the country, those bands may be licensed or license-exempt. In the latter case, the regulator might impose certain restrictions such as primary user, listen-before-talk, or a maximum continuous transmission time to enforce

[19] Bridges Edward. *Helios Towers invests in Democratic Republic of Congo mobile infrastructure*. 2018. url: `http://www.heliostowers.com/media/press-releases/2018/helios-towers-invests-in-democratic-republic-of-congo-mobile-infrastructure`.

the coexistence of multiple users. The advantage of the often costly licensed spectrum is that the license holder has exclusive usage rights. Whereas in the free-of-costs license-exempt case, multiple users might compete for the same resource which may affect the predictability of the channel and therefore crucial parameters such as capacity and latency. Such resource conflicts are less likely in rural areas and can be further minimized by proper spectrum planning and antenna configurations.

While higher frequency bands offer higher link capacities, the maximum link distance is shorter and the sensitivity to weather conditions increases. For instance, while 5 GHz links are nearly immune to changing weather condition, even light rain or fog may render 60 GHz links useless.

The setup of a directional link requires proper planning (line-of-sight, distance, compliance with licensing) which requires expert knowledge, but can often be done remotely. In the field, properly trained staff is required to conduct a site survey and then to eventually mount the equipment and to point the antennas at each other. Modern equipment often has built-in visual and audible cues to help finding the sweet spot (similar to setting up a TV satellite dish). For longer distances, these tasks may involve climbing rather fragile looking 30m or 50m towers and requires trained staff wearing proper protection gear.

After a successful installation, the equipment typically needs to be configured for a specific frequency (licensed case) or to choose a *free* frequency (license-exempt case). Other parameters to be configured include the regulatory domain (maximum transmit power, possible restrictions, etc).

The equipment is typically sold in pairs to set up a single link. If more complex network topologies are needed, additional networking equipment (switches, routers) may be required. The configuration or the replacement in the case of a failure may require an expert on-site.

To decrease the costs for the required poles, landmarks or public buildings should be considered. In addition, by using solar power and choosing energy-saving equipment, the need for a stable power grid at any location can be eliminated. Directional wireless networks can greatly decrease the deployment costs for suitable topologies to provide Backhauling or even replace fiber Backbones in rural areas.

Directional wireless links are typically used to provision mobile base stations, WiFi access points or to fulfill the communication needs of businesses, schools, etc which in turn provide their their own access solution (i.e. Ethernet, WiFi, LTE).I

Segment	Favored	QoE	Costs	Supplement	TRL	Remarks
Backbone	✗	–	$$	Fiber	++	
Backhaul	✓	+	$$	Fiber	++	
Last Mile	✗	+	$$-$$$		+	CPE

Table 2.8: Directional Wireless (Licensed, License-exempt, mmWave)

2.8 WiFi Mesh / HotSpot

Wireless Mesh Networks (WMNs) differ from other network architectures (P2P, P2MP) in that no direct physical connection between the communication partners is required, similar to the way the Internet works as a whole. Mesh routing protocols automatically ensure that the traffic is forwarded to the destination by determining the best route in the network. Such protocols also react to link or node failures by finding alternative routes.

In most cases, WMNs operate in license-exempt bands using off-the-shelf WiFi routers which greatly reduce the overall costs. In addition, due to the decentralized protocol design, WMNs are especially well suited for small community networks since they do not require specialized staff. However, depending on the number of uplink connections to the Internet, important links in a WMN can quickly become a bottleneck. In the most common and easy-to-use design, wireless mesh routers are equipped with only one radio and a single channel is used for all communication. This significantly affects the performance for larger networks or under heavy load. Especially streaming services pose a major challenge and such single-radio devices should not be considered.

Dual-radio mesh networks are increasingly being used to soften this capacity issue by dedicating one radio as an uplink and one radio to Access (HotSpot). An obvious approach to further enhance the performance are multi-radio mesh networks which operate at the *best* channels among peers. The management of such systems is far more complex and typically requires sophisticated protocols and alghorithms to ensure a stable operation. Compared to a single mobile network macro cell, several small mesh networks interconnected via high-speed directional wireless links can provide comparable capacity to each user but are more difficult to set up and maintain since the increased number of nodes and systems adds complexity.

Single- or dual-radio WiFi Mesh networks can be a cost-efficient alternative Last Mile technology where low costs are more important than per-user capacity. Properly designed, they are suitable for community networks where users become the operators of their own infrastructure. Freifunk user groups in Germany and many other initiatives around the world using WiFi Meshes for extending connectivity and are well-known examples of OpenSource/OpenHardware WMN and HotSpot solutions.

Note, this section does not consider larger in-door WiFi-Access point solutions, as they typical require a managed Ethernet and/or fiber network in the background.

Segment	Favored	QoE	Costs	Supplement	TRL	Remarks
Backhaul	✗	–	\$\$-\$\$\$	Directional Wireless	±	Multi-Radio nodes possible
Last Mile	✓	±	\$-\$\$		+	Maybe CPE for in-door coverage

Table 2.9: WiFi Mesh / HotSpot

2.9 Conclusion on Technical Options

Concluding this overview of possible technological solutions, Figure 2.3 provides a ranking for typical rural scenarios. To allow for a comparison of well-established and novel solutions, this Figure focuses on the expected Quality of Experience and the costs of each respective technology in relation to its Technology Readiness Level (size of the bubble).

Where feasible, fiber is clearly the technology of choice. For the Backhaul segment, Directional Wireless provides the best QoE/cost ratio while as a Last Mile solution WiFi Mesh or Cellular offer the best QoE/cost ratio, each with respect to their respective TRL. The QoE provided by most TVWS solutions seems rather limited for longer-term Backhaul deployments, but may be sufficient in certain use cases. As of September 2018, the available information on Airborne and LEO/MEO systems is insufficient and the information provided here should be considered as tentative.

As a general recommendation, smaller high-bandwidth cells in sub-GHz spectrum should be used to provide Access including in-door coverage without the need for a CPE. Prospective stakeholders should work with national regulators towards this goal. A similar point of view is taken in a recent ITU report on 5G in rural areas: "...Local authorities and regulators

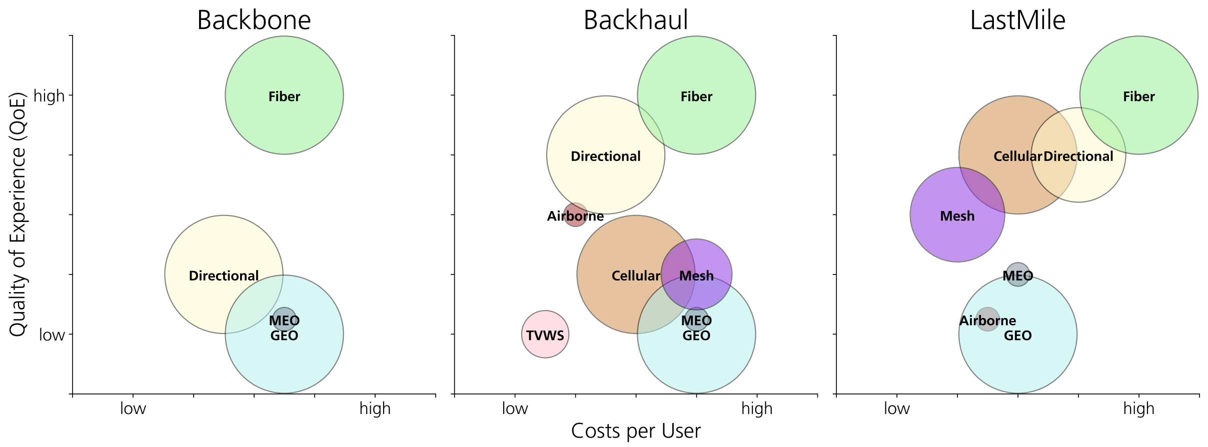

Figure 2.3: Overview of the key performance indicators of the discussed technologies in the three distinct network segments. The size of the bubble represents the TRL.

should recognize the risk of increasing the digital divide and support commercial and legislative incentives to stimulate investment in affordable wireless coverage through sub-1 GHz spectrum, where possible...".[20]

From both a purely technical as well as UE penetration point of view, 4G/5G data networks in sub-GHz spectrum could be the technology of choice for the Last Miles incl. in-door coverage. **However, the affordability of a cellular solution highly depends on the costs of the equipment, a possible waiving of the royalty fees, as well as a supportive spectrum-licensing scheme.**

3 Regulatory Aspects

As highlighted in the introduction, in order to bring the **other half** online, new technologies and organizational models should be considered. Most regulatory and policy frameworks focus on the provision of broadband Access primarily by a limited number of large national operators. This presents barriers to other models of Access that could complement the existing players, whose business models are less able to cost-effectively serve remote and sparsely populated areas [21]. Some regulatory agencies are already starting to support new strategies, e.g. at a regional level, the Inter-American Telecommunication Commission (CITEL)[22] and Communications Regulators' Association of Southern Africa (CRASA), and at a national level, countries such as Mexico,[23] Argentina,[24] and South Africa.[25] The following sections describe the current policy and regulation landscape and

[20] Brahima Sanou. *Setting the Scene for 5G: Opportunities and Challenges*. Tech. rep. 2018.
[21] More detail about the different business models is provided in Chapter 4.
[22] *Internet Society and the OAS through CITEL sign an agreement to bring the Internet closer to rural areas of the Americas*. 2018. url: `https://www.internetsociety.org/news/press-releases/2018/internet-society-and-the-oas-through-citel-sign-an-agreement-to-bring-the-internet-closer-to-rural-areas-of-the-americas/`.
[23] *Programa Anual de uso y aprovechamiento de frecuencias*. 2015. url: `http://www.ift.org.mx/industria/espectro-radioelectrico/programa-anual-de-uso-y-aprovechamiento/programa-2015`.
[24] *Resolution from the regulators to exempt Community Networks from licensing fees*. 2018. url: `https://www.boletinoficial.gob.ar/\#!DetalleNorma/190061/20180817`.
[25] *South Africa becomes the first country in the region to support community networks*. 2018. url: `https://www.apc.org/en/node/34705/`.

highlights interventions that could lead to frameworks that enable those novel technological and organizational models.

3.1 Awareness, Recognition and Credibility

One of the main barriers to the adoption of new models for Access provision is that only few people know they even exist. This applies not only to the rural communities that are most likely to benefit, but also to policy makers and regulators, and development cooperation organisations. When policy and regulatory frameworks are inherently conservative, it is difficult to bring about change when there is little evidence of the options, and few complementary operators to lobby governments or drive interest from other interested parties. Addressing this aspect is one of the key objectives of the APC/Rhizomatica project "Can the Unconnected Connect Themselves?".[26] Lack of awareness is compounded by an entrenched idea among most policy makers and financiers that only traditional national operators can provide services of sufficient quality, and at an affordable price. This view is partly due to the lack of knowledge about emerging alternatives, and because people from (disadvantaged) rural areas lack the ability to voice their concerns over the poor quality (or lack of) service provided by national operators in these areas.

3.2 Licensing

Telecommunications infrastructure deployment and service provision require licenses from the communications regulator. Most developing countries have yet to move to a modern unified regulatory regime based on technological neutrality and simple authorizations to permit service provision. Since national licenses are normally the only type available, and although a few countries like Brazil and India have adopted tiered licensing systems which provide licenses at the regional or municipal level, the requirements for these are still bureaucratic, and the technical and financial requirements are beyond the means of most potential operators. Concerted awareness raising about existing good practices, such as reducing the requirements and costs to provide services, deploy infrastructure, geographical scope of the licenses, together with capacity building work among policy makers and regulators, is needed to address this situation.

3.3 Access to Radio Spectrum

Due to the potential for interference when two operators use the same frequency, the use of most radio spectra requires a license. Similar to the licensing issues described above, smaller-scale operators often lack access to the radio spectra usually needed to provide services. This is largely because regulators predominantly regard spectra as a scarce resource that must be carefully managed through licensing and assignment processes. However, both the spectacular growth of WiFi through the (re-)use of the license-exempt spectrum bands and the lack of use of much of the licensed spectrum in rural areas indicate that this may not be the case. Also, new technologies such as radio devices which operate over a much wider range of spectrum bands using spectrum sensing or online databases of real-time spectra, suggest that regulators need to be made aware that a paradigm shift in spectrum management is taking place. In addition, as Mexico [27] has shown, special allocations to those interested in connecting the unconnected have had a great impact in

[26] *Local Access Networks: Can the unconnected connect themselves?* 2018. url: `https://www.apc.org/en/project/local-access-networks-can-unconnected-connect-themselves`.
[27] https://www.tic-ac.org/

remote populations. Here, prospective stakeholders could help to promote favorable conditions that will enable access to - preferably sub-GHz - radio spectra for operators connecting rural areas [28].

3.4 Access to Passive Infrastructure and Backhaul

Even with a license and access to spectrum, it is often impossible to provide affordable access in rural areas if there are no domestic backbones to provide backhaul connections or if backhaul is not affordable. Aside from limited competition in this area, this is also often because infrastructure sharing and dig-once policies are not in place to minimize costs and incentivize private operators to roll out pervasive fiber infrastructures. Some fiber is being deployed by governments, but it is often charged at excessive rates to operators, instead of pricing it as a public utility/enabler. Similarly, access to existing passive infrastructure, such as the towers of mobile operators, the masts and poles of public broadcasters, and energy distribution grids, should be more affordable to extend Access. Promoting and enforcing clear guidelines and transparent pricing models for infrastructure sharing will contribute to this end significantly.

3.5 Access to Network Information

Even if fiber is available nearby, it is often very difficult for a new operator to request information about the nearest point of presence, to design the network while striving for robust and cost-effective solutions. It is also difficult to know who owns allocated radio frequencies that might be unoccupied or unused in rural areas. Similarly, access to information on tower locations is needed so both governments and other actors can identify the connectivity gaps and adopt the best approach to bridge them. Strategies to make this information public and open will enable more stakeholders to participate in looking for solutions to close the digital divide.

3.6 Taxation and Services Provisioning

Lastly, there are many taxes that add to the burden of setting up and operating networks. In some countries, import taxes are up to 40% of the total cost of the equipment. Other taxes include fees per mast and device installed and contributions to universal service funds, among others. These added costs must be recovered from end users, which further limits the service's affordability.

4 Funding Aspects

The following chapter discusses funding opportunities for potential stakeholders contributing to the financing of novel, alternative communication technologies; these include the incentive to reduce administrative burdens and costs, the challenges currently faced by financial institutions, as well as a description of financial and non-monetary stimulus measures to achieve rural networking. Finally, the chapter appeals to potential actors to take measures to build a large-scale funded network in rural areas, as a clear precedent would help to incite replication at international level.

[28]https://www.internetsociety.org/resources/2018/unleashing-community-networks-innovative-licensing-approaches/

4.1 Reduction of administrative burdens and expenses

Due to the limited return on investment in connecting remote and rural areas, much of the funding required to extend access has been provided thanks to projects from the International Financial Institutions (IFIs) – often through grants and soft loans to governments and commercial operators. As discussed in the introduction, the business models that made this possible are unlikely to be the same for connecting the unconnected. In this new landscape, IFIs play an important role and could have a major impact on the viability of innovative technical and business models for reaching the unconnected by supporting the following measures:

- Ensure that finance for traditional infrastructure (roads/rails/powergrids etc) include the small additional cost of ducts[29].
- Finance for traditional infrastructure should also be contingent on inclusion of sharing clauses for rights of way and tariff caps on the cost of leasing passive infrastructure, including towers, high sites, ducts in roads, etc [30].
- In financial negotiations with Ministries of Finance, encourage tax and import duty breaks on Information and Communication Technologie (ICT) equipment for rural areas to facilitate affordability of services [31].
- Establish funding mechanisms which can also disburse to smaller connectivity players (more on this below).
- Finance the extension of national fibre backbones and shared towers into rural areas to help reduce backhaul costs.
- Promote inclusion in policy maker capacity building programmes the support for the full range of technical and business models for connectivity initiatives

4.2 Challenges and opportunities of funding alternative solutions

The novel business models of many innovative initiatives face limited direct financing avenues, which are, together with the regulatory and awareness barriers outlined above, among the key reasons for the limited extent of rural deployments. There are three intrinsic difficulties faced by institutions financing developing country networks focused on remote and rural areas:

Scale: In most cases, rural networks are likely to have much fewer customers than urban network deployments, rendering them less attractive to traditional investors or lenders, be they commercial or soft (development) funders.

Real and perceived levels of risk: There may be higher actual and perceived levels of risk by potential funders because the initiatives are relatively novel, may be run by people with limited business skills, or use new technologies or business models in unfamiliar contexts. These initiatives may also lack other asset sureties needed to provide guarantees for loans. In many developing countries, the cost of commercial bank loan finance is also relatively high, so this option is infrequently used.

Lower potential returns on investment: Networks serving remote and rural areas can be expected to have a low ROI because they usually operate in locations with low-income levels, and

[29] Current estimates indicate that adding a duct to a road project increases the total budget by 1–2% (Mike Jensen. *Unlocking broadband for all.* Tech. rep. APC, 2015)

[30] https://www.apc.org/en/tags/infrastructure-sharing/

[31] https://www.gsma.com/mobilefordevelopment/connected-society/affordability-and-taxation/

where operating costs are substantially higher in comparison to urban areas. As networks need to try to ensure that fees for service are as low as possible, potential profits for private investors, who may not be incentivized by the potential downstream economic benefits, are limited.

Given the considerations above, soft loans, grants and development funds are likely to be particularly important avenues of finance for "connecting the unconnected". In addition, local intermediaries acting for many networks are likely to play a key role in this area as they may be more familiar with the landscape and can thus better evaluate potential initiatives, aggregate needs, as well as disburse funds received from large funding sources.

4.3 Financial and non-monetary stimulus measures

Aside from the traditional bilateral and multilateral development institutions such as national development banks or UN agencies and organisations such as the World Bank and the IFC, many other stakeholders should be encouraged to consider creating funding vehicles for rural connectivity:

- National governments often have Universal Service Funds (USFs) to support the provision of access in rural and underserved areas. Many of these have already accumulated large amounts of unspent funds, partly because of the limited capacity of regulators to evaluate and disburse funds to the right projects, and also because of the paucity of appropriate projects to support.[32] Apart from financial support, prospective stakeholders could help with the proper legal and regulatory establishment of such funds. Aside from simple direct grant or loan funding, another vehicle is the Least Cost Subsidy Auction where government calls for expressions of interest in serving a location and accepts the one with the lowest proposed subsidy[33].
- Grants and awards from Regional Internet Registries, ccTLD operators, the Internet Society, APC and other international Non-Governmental Organizations (NGOs) and commercial tech organisations such as Facebook, Microsoft and Mozilla: Although insufficient to address the size of the problem, a number of networks have received startup or scaling funding and operational support from these sources.
- Crowdsourced funding. In cases where telecom infrastructure is managed as a common-pool resource, investment is crowdsourced by those benefiting from the infrastructure (see guifi.net, which won a European Commission Broadband Award with this approach). Crowdsourcing also offers significant though untested potential from the diaspora and people in developed countries who have visited the area as volunteers or tourists.
- Provision of in-kind services: These can reduce the startup and operating costs of the network. Examples include donation of equipment, skills/training, and backhaul capacity/bandwidth from local or foreign research and academic institutions, Corporate Social Responsibility (CSR) programmes of businesses, and NGOs specifically sourcing tech volunteers.
- Cross-subsidization: In some cases, networks may be financially sustainable by charging businesses a monthly fee with discounts given to the public. Funds for the cross-subsidy can also come from other services provided. These can also be services unrelated to the provision of connectivity to the end-user, for example, in remote areas, hosting remote sensing equipment (weather, air quality, etc.) for a government or research agency.

[32] Thakur and L, *Universal Service and Access Funds: An Untapped Resource to Close the Gender Digital Divide*.

[33] More information available here: https://www.repository.law.indiana.edu/cgi/viewcontent.cgi?article=1531&context=fclj and here: https://lirneasia.net/2007/03/india-auction-viable/

4.4 Clearing the hurdles

The above mentioned alternative measures and approaches may differ significantly from what larger public institutional funders are acquainted with in terms of the size of the projects or typical project viability or credibility assessment schemes. In order to fund connectivity for the other 4 billion, those concerns should be addressed by, for example, the introduction of credible partners that can provide capacity building for local network operators, or provide legal and administrative support. The recipient government (regional / state / national) should clearly support such projects by ensuring spectrum license fee exemptions, reduced taxes or tariffs, proper infrastructure-sharing regulations and co-funding (i.e. via USFs).

5 Novel Operator Concepts

Novel technologies and new thinking in the regulatory and financial domains can allow for improvement of existing operational models, but also enable completely new business models to meet the needs of rural areas in particular and to bridge the digital divide.

Large nation-wide (mobile) operators have been struggling to apply their rather *grown* business models to (very) low-income rural areas. Initially, those models and the underlying technology have been designed for deployments in more developed, higher income, and more densely populated areas where access to a stable power grid could be assumed, connectivity to the backbone was possible with reasonable means, and highly skilled technicians are available to set up, maintain and operate such networks. Furthermore, their business processes are often inflexible and tend to support larger homogeneous segments of the market where most profit can be made quicker, while **rural areas are much more diverse and have specific technical and financial challenges**.

In order to adapt their networks to rural environments, operators have been deploying extended range (up to 30km) GSM (2G) cells, which typically leads to reduced service offerings and a focus on low-bandwidth voice and Short Message Service (SMS). Such cell towers are then often supported by a massive battery backup or via a diesel generator which requires periodic refueling and, generally, burns fossil fuels. The power consumption of a cell site is in the range of hundreds of watts for the technology alone; additional hundreds of watts are often required for actively cooling the equipment. **Reducing the energy footprint of the equipment as much as possible is therefore a key requirement**.

The authors have been in meetings with operators where "ultra-low cost" 5G scenarios have been discussed and the economical feasibility (CAPEX + OPEX + gain) has been analyzed based on the Average Revenue Per User (ARPU) of the areas to be covered. For rural areas in many sub-Saharan countries an ARPU of about 2 USD was assumed which operators seem to be unable to meet with their current concepts.

Therefore, we present here disruptive approaches which are specifically tailored to the requirements, needs and possibilities of low-income rural areas in developing countries. Many projects worldwide have been experimenting with alternative solutions. Some are in active pilot deployments. The authors are involved in such projects in various fields. In the following, we present a concept for each, the **Backhaul** and the **Last Mile** network segment and provide **Best Practice** recommendations or **Lessons Learned** information.

5.1 Common Aspects

Regional, smaller ISPs are able to meet local needs better and are often enabled by emerging technologies. They know the specific local requirements and are very well connected with local stakeholders such as municipal managers, local government, farmers, schools as well as the inhabitants - their potential customers, but also potential supporters who might contribute resources such as locations to mount equipment or electricity. The local ISP or his staff typically live in the provisioned areas themselves and hence are intrinsically motivated to provide and maintain a sustainable solution. If problems occur, they are readily available and can quickly react.

A local ISP cannot employ a pool of highly trained technicians or experts (availability and costs), hence potential technologies must be easy to deploy and maintain (plug & play) to allow scalability of this approach (expert support possible from remote). Proper documentation (text and videos) should provide blueprints for planning and execution. To further decrease the costs, such equipment could build upon **OpenSource** software and **OpenHardware** designs.

5.1.1 Open Source and Open Hardware

Alternative approaches often build upon readily available hardware and software components exploiting the economies of scale. Those might be commercial products as offered by companies such as Ubiquity or Mikrotik, or OpenSource and/or OpenHardware solutions, such as LibreRouter [34] or the Turris Omnia [35] or custom-made designs building upon the former.

The word *Open* here typically means that the creator of the technology makes his design free to use or even free to modify and enhance by other parties. Thus, the use of such technologies does not incur license fees. Furthermore, many volunteers worldwide participate in the development efforts and contribute manpower which could hardly be paid for. While this often yields good performing technologies, there is often only minimal *high-level* documentation, no guarantee of any sort, and no technical support to call for help. Hence, to make such solutions widely deploy-able and to maintain them while keeping track with future developments, **a team of highly skilled engineers should design, document and maintain blueprints for OpenSource and OpenHardware networks**. Such a **team** could be established in the form of a not-for-profit entity such as a a foundation - here referred to as the 'Connecting the Unconnected Foundation (CUCF)'. Products being built upon Open designs pose questions about liability and compliance with national regulatory requirements. Especially with radio hardware, there is an additional question regarding conformance with regulatory requirements and, for example, FCC or CE certifications. Such issues should be addressed by the CUCF to ensure that local ISPs can build upon compliant and trusted solutions which could ultimately receive external funding.

While OpenSource developments are powering multi-billion businesses, OpenHardware is still in its infancy and clear paths towards adoption of such developments (including certifications, conformity, long-term support, quality of materials, etc.) are yet to be proven. When comparing cost-effective OpenHardware solutions with commercial or operator-grade products, it is important to clarify all relevant requirements and parameters to conduct a fair and trusted comparison. This process should include reconsidering all those (sometimes *grown*) requirements and parameters to avoid limiting the selection unnecessarily.

[34] https://librerouter.org
[35] https://omnia.turris.cz/en

5.1.2 Business, Regulatory and Legal Aspects

Similarly, on the business or legal side, there must be well documented and legal-proof examples of business cases and procedures to set up and run such an ISP as a company which can pay for the costs of living of the founder, its staff, as well as the required network infrastructure and its maintenance and operation. Such procedures must cover all necessary steps from obtaining a reliable backbone connection via setting up backhaul and access networks to, eventually, the collection of payments.

Regulatory aspects regarding novel operator concepts have been discussed in Section 3. Blueprints of regulatory steps should be developed and maintained by the experts under the CUCF umbrella to ensure that local ISPs meet the requirements outlined in the national regulatory and policy frameworks as this is a key requirement to receive external funding.

The CUCF as an interdisciplinary entity could be funded from revenues of prospective stakeholders such as the local ISPs or by international donors, development cooperation, etc. Examples for such approaches are the Linux kernel [36] development or many other very successful OpenSource projects where paid experts drive further development and maintain a consistent code base which is relied upon by large cooperations and enthusiasts alike.

In addition, there are many rural connectivity pilots that reached maturity and are moving, or have moved, into a scaling phase. Their approaches and solutions should be evaluated and incorporated into the proposed blueprints.

5.2 Cost-Efficient Backhaul

Addressing the challenges in rural areas, Fraunhofer has been developing its self-managed, highly-integrated WiBACK [37] (Wireless Backhaul) technology to provide an alternative solution for the Backhaul segment to support local Last Mile access networks. The WiBACK approach builds upon concatenated, long-distance (up to 20km per hop) Directional Wireless links but can also integrate other technologies (such as dark fiber segments) if available in the deployment area. The design goal was to minimize the technical expertise required for setting-up and operating such networks. Furthermore, the energy footprint should be kept at a minimum to allow for solar-powered operations. The equipment should provide a Mean-Time between Failures (MTBF) of five years or more, taking into consideration the often harsh environmental conditions (temperature, rain, dust). Cost-effective off-the-shelf components are used as much as possible and the required information to manufacture such hardware can be made available free-of-costs. With this approach, Fraunhofer intends to foster local human capacity building and the establishment of a local ecosystem around a localized network technology.

The technology builds on proven operator-like protocols (such as Multi Protocol Label Switching (MPLS)) and concepts and is optimized for low-latency operation (< 3ms per hop) and allows for coordinated End-To-End (E2E) Quality of Service (QoS)-aware resource sharing so that multiple local ISPs could share the same Backhaul infrastructure (network slicing) according to agreed-upon rules (service levels).

The feedback gathered and the lessons learned from initial deployments in Tanzania and Colombia as well as Germany and Italy have helped to steadily improve the system and to demonstrate the potential of this approach. Early adopters point out the low latencies in the network as well

[36] https://www.kernel.org
[37] http://www.wiback.org

as the low maintenance requirements and the "no-expert-required" and Plug-n-Play design as a main differentiator to alternative solutions. It enables them to offer voice and data services at a significantly lower OPEX [38].

In a cooperation between national regulators and Fraunhofer, the Mozambican Regulatory Authority (INCM) [39] teamed up with ARCTEL@CPLP [40] and Fraunhofer Portugal within the context of the Sustainable Villages for Development (SV4D) [41] project, aiming at promoting universal access to broadband communications and Information and Communication Technologies (ICT) to underserved communities, and therefore to mitigate the effect of digital divide in the provinces throughout the country.

INCM, ARCTEL@CPLP and Fraunhofer have deployed the first WiBACK-based SV4D pilots in the Mocuba and Alto Molocue districts, Mozambique, allowing locals to explore the digital world and further develop the population's access to ICT. The pilot comprises hot spots serving the local population in high schools, university campi, hospitals, teacher's training institutes, market areas, and local administration offices. These pilots target at building prototypes of sustainable villages, providing not only connectivity to those who once were unconnected, but also aiming at introducing new business models promoting the improvement of new economic opportunities based on ICT.

5.3 Local WISP

Community networks can be broadly defined as locally owned and operated networks and as a particular type of local WISP. They can be commercial or non-commercial, and ownership can be either by the community or an individual, as long as they are local to the communities they serve. There are instances of community networks all over the world, in both urban and rural environments, and in developed and developing countries. In the global north, there are several instances where community networks have ranked above traditional large operators in user preference.[42]

Community networks usually build on very cost-effective consumer wireless routers used as Mesh devices. While the extent of the scalability of these initiatives has yet to be fully tested, multiple flavors of such networks already exist around the globe, including in relatively well connected locations in Europe and North America [43]. A developing country example is Zenzeleni Networks [44], a non-profit organization that builds the capacity of rural communities to design and operate telecommunication businesses that they own themselves. Zenzeleni has connected 7000 people and 10 institutions using WiFi technology, offering prices many times lower than those offered by existing operators. WiFi is used both in the backhaul - 60 km to the closest fiber optic point of presence, as well as inside the communities where Wifi Mesh Devices are used to provide service to the end-user. Most anchor tenants are serviced via dedicated Point to Point links due to higher quality of service requirements. The CAPEX has been subsidized by a combination of donor funding and contributions from the anchor tenants. Currently, the OPEX is entirely covered by the users of the services provided. Zenzeleni Networks Mankosi is a 100% Black Owned, 40% women, telecommunications co-operative that has been legally sanctioned by the regulator (ICASA). Two other co-ops are currently being supported to follow Mankosi's steps.

[38] Statement Servario CEO, Germany and BlazingSoft CEO, Colombia

[39] http://www.incm.gov.mz

[40] http://arctel-cplp.org

[41] https://www.fraunhofer.pt/en/fraunhofer_aicos/our_work/projects_/sv4d.html

[42] *People Still Don't Like Their Cable Companies, CR's Latest Telecom Survey Finds*. 2018. url: `https://www.consumerreports.org/phone-tv-internet-bundles/people-still-dont-like-their-cable-companies-telecom-survey/`.

[43] https://www.internetsociety.org/issues/community-networks/

[44] http://www.zenzeleni.net

In addition, when community networks are able to secure access to radio spectrum they can provide mobile phone services as well. For example, Telecomunicaciones Indígenas Comunitarias [45] (TIC S.A), a non-profit organization based in Oaxaca, Mexico, holds a regulatory concession as a social telecommunications operator, valid for the next 14 years. This entitles TIC to operate mobile GSM telecommunications services using reserved frequency bands. The permitted spectrum covers the Mexican states of Veracruz, Puebla, Chiapas, Guerrero, and Oaxaca, with an addressable population of between 3 and 5 million people. Currently TIC networks serve 3,350 active daily users spread across 63 villages and communities in the state of Oaxaca in southern Mexico served by 14 community-owned and operated cellular sites. Current operational sites generate around $6,200 USD of income for the organization (TIC) every month. TIC's monthly operating expenses are around $8,500 USD. The difference is covered by philanthropic donations and in the future by increased income from new sites. According to external studies, each year TIC networks save users and their families well over $1 million USD per year, creating over $600,000 USD in additional income for users, and saving the Mexican government $750,000 USD.

From a more qualitative standpoint, according to interviews with users and authorities, the networks increase security, community participation, access to information, small business development, access to services, and disaster mitigation.

6 Conclusion and Further Considerations

Nearly half of the world's population is still unconnected and, especially people living in rural areas in developing nations are affected. While recent years have seen great progress in bringing more people online, the pace of network expansion - especially to rural areas - is expected to slow down and the connectivity goals set forth by the international development cooperation are going to be missed. A main limiting factor is that the technologies and business models in use are not well suited for rural areas, which are difficult to connect and often provide little revenue potential. However, there are numerous novel developments promising significant potential to bridge the Digital Divide. These include technological alternatives for established telecom operators as well as completely new actors alike. Additionally, new operator models, enabled by such alternative technologies that include and are based on local communities, provide new options and new definitions of "profit" - where affordable Access is the profit for communities instead of the financial ROI.

These developments have been well received and have often shown promising results in initial pilots or smaller commercial trials. However, there are still hurdles hindering the scale-up from these pilots. While in some cases the technology is not yet mature or still too costly, often regulatory issues are the limiting factor. This holds also true for the newly enabled operational models. May it be the availability or cost of a radio frequencies license or insufficiently regulated markets which prevent new entrants, such as local communities, from gaining Access to the Internet Backbone or existing ones from being able to extend their network into rural areas. Further challenges include the lack of skilled labor as well as the lack of access to financial means, helping to bear the significant costs for bringing Access to rural areas.

Connecting the unconnected is a broad topic with various facets and many actors need to come together to ensure sustainability. Apart from the discussion on various technical aspects (see Chapter 2.9), this White Paper identifies the following fields of action for rural connectivity:

Regulation: One of the main barriers for the development and implementation of new solutions are regulatory issues. As pointed out in Chapter two, a key aspect to affordable Access in rural

[45] https://www.tic-ac.org/

areas is the use of the sub-GHz spectrum. Development cooperation should help to introduce fair and supportive regulatory regimes to enable sustainable networks in rural areas.

Piloting: The first steps are always the hardest. Development cooperation could help with setting up pilots of novel concepts, supporting evaluation campaigns to ensure replicability and scale-up in other regions. Such pilots may exploit resources of existing development cooperation projects in need of connectivity. Development cooperation could provide financial support and help with approvals, permission, and other regulatory issues. Eventually, proven pilots can then serve as blueprints for other regions and scales.

Financing: Prospective stakeholders continue to play a major role in investments to build up sufficient Backbone capacity. Furthermore, stakeholders could actively get involved in the selection and piloting phases of novel concepts and technologies by contributing their views on how such concepts could reach a maturity that qualifies them for financial support.

Scalability: The scale-up of proven concepts requires regulatory groundwork as well as established funding schemes and possibly support regarding royalty burdens. Furthermore, local human capacity is required to drive the deployments in the field.

Cost of equipment: Networks are infrastructure projects which require investments in equipment and licensing or royalty fees. The use of most practicable solutions built from readily available Commercial Off-the-Shelf (COTS) components should yield reduced equipment cost. Local production and maintenance can help to foster the development of local ecosystems and human capacity building. Some technologies are loaded with significant royalty fees; prospective stakeholders may be able to reduce such load to enable business models in very low-income areas.

Skills: The lack of skilled labor is a main driver for operational costs especially in rural areas and also a limiting factor for further deployments. While technologies which reduce maintenance efforts can be promoted, teaching the needed skills should be an integral part of the solution.

Novel communication technologies and concepts are at a decisive stage and could greatly enhance the interconnectedness of individuals and thereby enrich the lives of people in rural areas. Promising technologies are raring to be tested and extensively implemented in the real world. However, they require third-party support to meet the multi-layered needs of modern industry, comprising the readiness of their technology, regulatory compliance, and adequate funds to implement larger-scale projects.

List of Abbreviations

ARPU Average Revenue Per User
CAPEX Capital Expenditure
CATV Cable Television
COTS Commercial Off-the-Shelf
CPE Customer Premises Equipment
CRASA Communications Regulators' Association of Southern Africa
CSR Corporate Social Responsibility
CUCF Connecting the Unconnected Foundation
DSL Digital Subscriber Line
E2E End-To-End
FTTC Fiber-To-The-Curb
GEO Geosynchronous Earth Orbit
GSM Global System for Mobile Communications
GSMA GSM Association
HAP High-Altitude Platform
ICT Information and Communication Technologie
IFI International Financial Institution
IPR Intellectual Property Right
ISP Internet Service Provider
ITU International Telecoms Unions
LEO Low Earth Orbit
LTE Long Term Evolution
MEO Medium Earth Orbit
mmWave Millimeter Wave
MPLS Multi Protocol Label Switching
MTBF Mean-Time between Failures
NGO Non-Governmental Organization
NLOS None Line of Sight
OPEX Operational Expenditure
OTT Over-The-Top
P2MP Point To Multipoint
P2P Point To Point
QoE Quality of Experience
QoS Quality of Service
ROI Return of Investment
SDG Sustainable Development Goal
SMS Short Message Service
TIP Telecom Infra Project
TRL Technology Readiness Level
TVWS TV White Space
UE User Equipment
UN United Nations
USF Universal Service Fund
WiFi Wireless Fidelity
WISP Wireless Internet Service Provider
WMN Wireless Mesh Network

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