Overview

In May of 2011, the United Nations declared internet access a basic human right. While we have made great strides, 53% of the global population still lacks access [1]. This is an amazing proliferation, up from the 1% of the population that had connectivity back in 1995, but there are still 4 billion unconnected people. While 75% of people aged 15-24 have access to the internet [1], there are huge disparities in access. Regions with highest offline population are Africa (75%), the Arab States (58%) and Asia-Pacific (58%). The exclusion rate in those regions is worse for the female, rural, poor, illiterate and elderly populations [2]. Several reasons determine the absence of the service, but the largest challenge on the supply side is the infrastructure required. On the demand side digital literacy, the gender gap and affordability remain significant hurdles. In this article, we explore diverse trends, projects, technologies and initiatives with focus on expanding and enabling access with a cost-effective approach.

What is Broadband?

The first thing we need to discuss is the definition of internet access. What services and speeds constitute access? Much of the recent increase in access in lower and middle income countries, hereafter LMICs, is due to the rapid adoption of mobile phones. Network access is continuing to expand as well as costs for both the mobile hardware and data plans are continuing to drop. This has led to a 30-50% growth rate in mobile broadband subscriptions in LMICs over the last five years [1]. In 2015, the Pew Research Center found that smartphone ownership in LMICs had reached 37% [3].

While there has been great progress in mobile access, LMICs are behind in fixed broadband access with only 6% of the population having access to speeds of greater than 10 Mbps [1]. Without China included, the percentage drops to 1.6% [1]. For perspective, in the United States the FCC recently raised the minimum speed that qualifies as broadband from 4 Mbps to 25 Mbps [4], while India has declared that the minimum is 2Mbps [5]. ITU specifies that 256 Kbps or greater qualifies for fixed broadband for their research [6]. Countries and organizations that track connectivity lack a standard definition for broadband. The speeds that qualify as broadband vary from country to country and study to study. Meanwhile, bandwidth required for internet content will continue to increase and lower speeds will limit the applications one can use. For example, an average HD movie is 3-5GB. At 256 Kbps a 5 GB file download would take almost two days to download. Another example is video chat. Skype requires 128 Kbps for a video call and 1.2 Mbps for an HD video call. If you add multiple people to the call, each stream adds additional bandwidth requirements.

Mobile internet penetration continues to grow with up to 85% of the world's population covered by current cellular infrastructure [7]. While some areas still utilize 2/3G technology, most carriers are in the process of phasing both 2G and 3G technology out [8]. As 4G/LTE coverage continues to expand across the globe, mobile data rates continue to climb. Currently the performance ranges from 2 Mbps to over 40 Mbps in certain countries [9]. Proposed 5G performance standards would deliver over 100 Mbps [10]. At these speeds, the line is blurred between traditional broadband and mobile internet. However, delivery of these speeds will require significant infrastructure investments and the internet backbone capacity will need to increase, especially in LMICs.

The Problem

While there has been progress on making internet access more affordable and accessible in LMICs, the results are still lacking. Since most governments and organizations measure internet access as 256KB or greater, there is still a gap in the performance and bandwidth of the access available. Only 6% of the population of developing nations have internet speeds above 10 Mbps [1]. Reliability and performance can dramatically influence the potential uses of the internet. There are direct correlations to increased connectivity and positive economic impact [2]. Mobile technology is helping LMICs expand access with reduced infrastructure costs, but fixed broadband availability and backbone capacity is required to reduce the inequity in the quality of service.

Conventional approaches by the established telecoms will not allow us to close this gap. At least 60% of the unconnected population live in rural areas [1], which means sparsely populated communities and households that will not fit the current business model for cities and highly dense settlements. There are numerous challenges in deploying to rural areas where the low population density means that infrastructure costs are higher and the return on investment is lower. **In this sense, the most urgent need is to find solutions to connect the large rural offline populations at minimal costs**. LMICs need significant investment and improvement in both the backbone and last mile infrastructure. The solutions exist to solve the connectivity issues we face. We require governmental policies that encourage infrastructure planning and investments, sustainable business models and training to increase digital literacy.

The traditional telecommunication providers continue to expand markets and add subscribers, but due to some of the logistical challenges mentioned before, it is not economically viable or feasible to expand access with traditional telecom infrastructure. Telecommunication companies have a statistic for average revenue per user, hereafter ARPU. Due to the high costs of infrastructure to serve the rural areas, the ARPU is significantly lower [11]. Understanding your market, developing a sustainable business model along with government policies, such as a universal access fund, are critical to the success of rural broadband deployments.

Two of the largest economic barriers to internet access are infrastructure cost and income disparity of people living in underserved markets. The Alliance for Affordable Internet, hereafter A4AI, sets their target for affordable internet as 1 GB for less than 2% of average income [12]. Similar to A4AI, the Broadband Commission for Sustainable Development sets target costs for connectivity at 5% or less of overall income [13], but that is difficult in populations living on less than one dollar a day [14]. Unfortunately, the pace of internet penetration is slowing down according to the latest A4AI report. Originally the world was projected to pass the 50% threshold in 2018, but due to governmental policies that are going in the wrong direction and higher than expected infrastructure costs, the timeline has shifted to 2019 [15]. While infrastructure cost hurdles can be addressed with innovations and investment, income inequality is a far more complicated issue.

Much of the focus and effort by those trying to reduce the inequality of internet access globally is on infrastructure. While that is a critical component, the demand side issues are often lost as we try to engineer our way out of the problem. While up to 85% of the world's population has connectivity options [7], less than 50% of the world is using the internet. There are many complex reasons for this, but digital literacy is an important part of the solution. In LMICs women are 13%

less likely to own a mobile device and cultural issues and digital literacy are significant barrier [16]. Again, we struggle with the definition of what is digital literacy. There are frameworks to measure digital literacy, but without standardization, the data across research projects is not as useful as it could be. Connectivity projects need to have a digital literacy component, or we risk the digital divide widening, even as availability increases.

Technology Trends

While barriers to access remain, there have been significant improvements in access. Again, most of these are due to the mobile revolution, but there are concerted efforts from governments, business, and nonprofits to increase accessibility. There is no silver bullet to close the digital divide, and there are wide varieties of solutions ranging from technology innovation, community involvement, policy and new business models that are attempting to close the gap.

TV White Space

One of the more established technologies is utilizing TV white space, hereafter TVWS, a technology that takes advantage of unused frequencies normally used for television broadcasts at the lower end of the spectrum. TVWS is attractive for rural underserved areas due to its low operating and capital investment, range and line of sight is not required for use. Since TVWS operates at a lower frequency than typical cellular or wireless internet, it can travel through walls and vegetation for up to 25-35 kilometers depending on the radios and line of sight [17]. TVWS has great potential to function as both a backbone and last mile delivery of communication networks, and to enable access in remote regions. Several groups, including the WhiteSpace Alliance, Microsoft Research, ITU, Digital Spectrum Alliance, and many others are actively researching and piloting TVWS networks to connect remote areas.

One of the groups that is developing and deploying TVWS technology is Gram Marg. Based out of IIT Bombay, Gram Marg is attempting to solve the last mile issues in rural villages in India. IIT Bombay has prototyped a backhaul network over UHF band that would be able to reach rural areas not within 5 km of the fiber backbone or areas with dense populations that require throughput greater than what current technologies provide [18]. They currently have seven villages within a 100 km of ITT. Utilizing the unused frequencies will enable clusters of village Wi-Fi networks or cellular towers to extend much further into remote regions without the cost of additional fiber installation.

Africa also has several projects utilizing TVWS technology. There have been trials in South Africa, Kenya, Malawi, Nigeria, Ghana, Botswana, Namibia, and Tanzania. Due to low penetration rate of high-speed internet, the lack of infrastructure that is common in Africa and the amount of people who live in remote regions, TVWS technology could be game changing if policy and cost concerns can be addressed.

As a part of its 4Afrika initiative, Microsoft Research has held 15 TVWS pilots across Africa. The largest deployment of TVWS technology in terms of square footage of coverage to date was in Namibia. Citizen Connect brings access to three regional councils, including 28 schools in northern Namibia [19]. In Kenya, they collaborated with Mawingu to provide both hotspot and home Wi-Fi access with a pay as you go model. The solar powered base stations also allow users to recharge their phones or tablets. There are currently over 400 hotspots in service [20]. In South

Africa there have been several trials in partnership with TENET sponsored by Microsoft, Google, IEEE and others with the goal of connecting schools with high speed internet. In one of the trials in South Africa, the University of Cape Town connected ten local schools to high-speed internet. Another project with the University of Limpopo connected five rural schools in the Limpopo Province [21]. All of these projects provide 2-10 Mb internet access at low costs and with bandwidth that is currently unavailable in most remote areas.

In the Americas, there have been trials and deployments in most countries. In Uruguay, Plan Ceibal collaborated with Microsoft and 6Harmonics to connect five remote schools with plans to expand to additional schools [19]. Columbia is the first country in Latin America to regulate TVWS in 2017 [22]. Global Broadband and Innovations Alliance is implementing TVWS in Jamaica to connect rural communities [23]. In the US, 23.4 million people lack high-speed connectivity. From Wyoming to West Virginia, there have been several TVWS deployments to attempt to solve the last mile problem of distributing internet access to rural areas with low population densities [24].

TVWS could be a solution to bridge the last mile connectivity from the communications networks to rural areas. Trials and implementations are currently active worldwide. To reduce the current access and performance divide it will take further investment and policy work to determine the areas where TVWS technology can be useful.

Balloons and Drones

There are several technology companies entering the ISP marketplace seeking additional users as traditional markets have become saturated. Google, Facebook, Microsoft and others have actively pursued internet connectivity for the unconnected with the goal of adding additional users to their base as well as having the benefit of providing social good.

Alphabet's Project Loon is a project to create a network of high altitude balloons that fly in the stratosphere and deliver internet access using LTE radios. Alphabet does not provide the service directly. Instead, they partner with local telecommunications companies and act as an extension of the existing cellular network. The balloons are solar powered and can remain in flight for nearly 200 days. Each balloon can provide service to a ground area of about 40 km in diameter and the balloons operate in a cluster [25].

Project Loon has had several trials from New Zealand to the US. Their goal is to eventually use up to 300 balloons that fly around the 40th parallel to provide internet access to remote areas in the southern hemisphere [25]. They have signed an agreement with Sri Lanka to provide expanded access to the country and they have recently deployed balloons in response to natural disasters in Peru and Puerto Rico where infrastructure was heavily damaged. In Puerto Rico, the balloons were able to connect over 200,000 people to the internet [26] until infrastructure was repaired. The Loon technology has potential to fill in the gaps in cell coverage in areas that are very remote and costly to deploy traditional infrastructure.

The Facebook Connectivity Lab was initially developing solar powered autonomous drones to compete with Google's Loon project. Their Aquila drones function similarly to the Loon's balloon

concept, but they are capable of powered flight. While they have stopped internal development on their high altitude drones, the project is continuing with partners such as Airbus.
While the Aquila drones attracted the bulk of the attention, some of the more interesting technology came out of the other initiatives within Facebook. In order to communicate between the drones and ground stations the drones used high data rate lasers or millimeter-wave radios that are capable of up to 40 Gbps of bidirectional bandwidth [27]. They have also developed a network planning tool and Terragraph a high frequency multi-node wireless system designed for dense urban environments. As a part of the Telecom Infra Project they have also been active in the development of OpenCellular, which is an open source wireless access platform.

While Google and Facebook's attempts have been ambitious and have made progress, the development of technology, like many other social impact projects before them, have had mixed results when it comes to impact. Loon was of great use to disaster areas, but most of these technologies have yet to get out of the lab to make a significant impact.

Satellite Constellations

While Loon and Aquila are trying to provide access to remote regions from the upper atmosphere, others are looking to provide internet access from low earth orbit, hereafter LEO. Satellite based internet has been around for a while, but latency and cost have always limited its usefulness. However, in recent years, several companies have been planning or have filed applications to implement constellations of satellites to provide internet globally. There are significant cost, regulatory and coordination hurdles to overcome if they are to have an impact on internet connectivity.

Latency, or the time it takes your network request to travel to the destination, will be a critical aspect in the success of a satellite constellation or any other connectivity project. Latency is traditionally measured in milliseconds and your internet experience is very sensitive to any increases in latency. A few things determine latency. First is physical distance and the speed that it takes a request to travel on the media. For example, a request to the E4C website, a packet from your cell phone, has to travel wirelessly to the cell tower and then traverse the internet backbone, then on to the destination hosting service. All of that happens in milliseconds or it will seem to take an eternity on the end device. Traditional ISPs (cellular, cable, DSL, etc.) ideally provide below 50 ms latencies to much of the internet. Even with fiber optic connectivity, you are limited to around 66% of the speed of light due to the refraction of the silica in the cable [28]. That means that a packet that travels from San Francisco to Kampala would have to travel that physical distance and would have much higher latency. Another factor in determining latency are all of the infrastructure and networks that are maintained by different providers in between you and your internet destination. The more hops required or any bottlenecks in the path will cause an increase in your latency.

One of the current limitations of satellite based internet and potentially one of the game changing aspects of the proposed LEO constellations is latency. Traditional satellite ISPs have been in geostationary or geosynchronous orbits, which are significantly higher than the proposed constellations, carrying with them much higher latencies. The LEO constellations reduce the latency by reducing the distance from the Earth's surface that the communication will need to travel. After the constellations are established, there is now a new benefit. As discussed earlier, our fastest connectivity on Earth is generally fiber optics and they are limited to around 66% of the speed of light [28]. In the vacuum of space, there is no such limitation. The satellites would be able to provide a new internet backbone as they communicate in a mesh network in space. For our example earlier, the packet would not have to traverse an undersea cable to reach from San Francisco to Kampala. Instead, you could connect directly to the satellite constellation or through your ISP and traverse most of the distance in the vacuum of space, then down to a ground station in Uganda. LEO constellations could potentially reduce latency, increase throughput and reduce overall costs.

There are still significant challenges to establishing a satellite constellation, but all of these benefits and potential revenue is encouraging several companies to enter the fray. This article is not going to list all of the contenders, but rather the ones that are the furthest along in terms of regulatory acceptance and prototyping.

OneWeb might be the first constellation in production with 720 satellites in LEO and up to 1,980 satellites in later deployments approved in their FCC application [29]. If all goes to plan, their initial roll out will provide broadband to Alaska in the first phase and connect up to 100,000 people lacking high-speed access, and the full constellation will be online by 2027 [30]. The first launch is scheduled for early 2019 with 10 of the OneWeb satellites aboard a Soyuz rocket in the first launch [30]. OneWeb has contracted with Arianespace for 20 additional launches that will have 34 to 36 of the micro satellite on each launch and will occur every 21 days after the initial launch [31]. All 720 satellites will be in orbit by early 2020 if the production, launch and implementation schedules hold.

So far, OneWeb has raised $1.7 billion USD in capital, but it is estimated that they will require $3-5 billion to fully implement the constellation [32]. Assuming that they can get over the financial hurdles, there are a few technical hurdles that remain. One is that OneWeb will not implement the satellite-to-satellite communication that would enable a new internet backbone in the initial deployment due to regulatory concerns [33]. Instead, they will rely on a system of ground stations for downlinks. This is due to countries wanting to be in control of the flow of data, not a technical limitation of the constellation as the satellites have the capability, but the hardware will not be installed [33]. This decision limits the latency benefits as well as having impacts on privacy, net neutrality and internet freedom.

Canadian based Telesat LEO is also trying to deploy a low latency LEO constellation. They might not be in service before OneWeb, but they were the first to launch one of their prototypes into LEO earlier this year. They had two prototypes, Vantage 1 and Vantage 2, but one of their prototypes was lost in November 2017 due to a failed Soyuz launch. Telesat is still deciding who they will contract to build the initial satellites. They plan deploy 117 initially, but the system can scale up to 512 satellites depending on business justifications, coverage and throughput needs [34]. They are targeting 292 satellites for the constellation to have full coverage and capacity. The 117 satellites in Phase 2 will begin deployment in 2020 and will enter commercial service in 2021 [35].

Unlike OneWeb, Telesat intends to implement the inter-satellite communication links that will enable the Telesat constellation to route traffic through space without the requirement to enter or exit through a downlink station. The satellite will be heavier than the OneWeb satellites [36] and will require more launches, but the added functionality will be a competitive advantage if they can get regulatory permission to proceed. Other competitors have filed complaints about satellite collisions in LEO, but the FCC has ruled so far that companies should be able to coordinate orbits and debris mitigation without further regulation at this stage.

SpaceX's Starlink may have the largest profile of all of these projects due to the company's other successes and its founder, Elon Musk's, popularity and the amount of publicity that draws. SpaceX has FCC approval and plans to launch 4425 satellites into LEO [37] to build out the Starlink constellation. Two prototypes, Tintin A and B, were launched in February 2018 and are currently testing the design of the satellites, the communications platform and downlink ground stations.

Starlink is projected to be online in 2021 with 800 to 900 satellites [38]. In order to fulfill the FCC application, SpaceX will need to launch 2200 satellites by 2024 and that is expected to cost between $10-15 billion USD for the entire deployment [39]. While that is a significant amount of money, unlike the most of their competitors, they own the launch vehicles to schedule and coordinate this massive effort. Starlink's goal is to provide gigabit internet access at under $50 USD a month per user and below 50 ms latency. That cost does not include the downlink station equipment or antennae, leading to more upfront costs, but that would be very competitive with any existing internet provider.

Much like OneWeb, Starlink will provide the inter-satellite communication that will enable a new backbone for internet communications. While it is still speculation, they are planning to go much further than other providers do when it comes to privacy and net neutrality. Elon Musk is claiming that the Starlink service will be IP-less and provide end-to-end encryption [40]. If these claims are true and the constellation receives the necessary government approvals, it would provide an alternative with much greater privacy and anonymity than traditional providers would. There is still the issues of having a physical downlink site located within a country and the likely restrictions or access that SpaceX would have to provide for the ability to operate within the country's borders.

LEO constellations could be a very attractive option to connect the remaining unconnected, but they have many hurdles to clear, from technical, financial, and regulatory, before they can be a legitimate option. While these will be difficult to overcome, there are hundreds of billions of potential revenue if one or more of these constellations come to fruition. If governments and nonprofits collaborate with these constellations, we could utilize the new backbone to reduce the number of unserved population as well reduce the cost.

While those were very large-scale projects, we are not focusing on the traditional telecom provider or government projects that are attempting to roll out or update infrastructure that will reduce the number as well. Now we are going to focus on smaller scale peer-to-peer, community and offline projects that are attempting to fill in the gaps where these large-scale projects cannot solve the problem.

Mesh Networking

Mesh networking is a combination of hardware and software that allows devices to communicate via a peer-to-peer network that is resilient yet inexpensive. It has been used in community networks and the internet of things relies on it for the small low powered devices to communicate.

There are several projects attempting to use different methods of mesh networking to connect to the internet in areas without infrastructure, to remain connected during natural disasters, avoid government censorship of the internet or provide secure communication without the need to use the internet. There are several projects or products in this area and we are going to focus on both hardware and software only solutions.

Several companies focus on mesh networking hardware for low connectivity environments and one of the more popular is the goTenna Mesh. This small hardware device connects to your smartphone via Bluetooth and broadcasts to other Mesh devices via UHF frequencies. The mesh devices have around a 6.4 km point to point range and about .8 km range in denser urban areas. The battery lasts about 24 hours with typical use and recharges in about 2 hours [41]. You can be in an area without connectivity and as long as you are in range of another Mesh device, you can still send a message, voice communication or emergency request. Your message will transmit across up to three devices and deliver it directly to someone in your party or externally through goTenna's message delivery service.

The goTenna Mesh has become very popular with the hiking and backpacking communities, but there have been issues with their use in disaster relief or development contexts. The Mesh device was inspired by the infrastructure damage inflicted by Hurricane Sandy, so it makes sense that they would get involved in the response to the devastating Hurricane Maria in Puerto Rico. They were planning to deploy up to 300 of the Mesh devices [42] in an attempt to build out a mesh network to connect FEMA resources, local emergency responders and city officials to coordinate the response. There are reports of issues with the deployment, with only around 80 of the devices delivered and the company has not responded to the issues [43].

There are similar devices to the goTenna Mesh, such as Beartooth, which has very similar functionality, but also includes a walkie-talkie, cell phone charging capability and built-in GPS. Sonnet is another competitor in the space, but it is still in development.

All of these devices have potential to provide connectivity in off grid areas, but they have limitations. The current target market is outdoors and backpacking enthusiasts, so the pricing is out of the reach of most of the unserved population in LMICs. They also suffer from a lack of standards. None of the products is interoperable, meaning that there must be an established network of devices to provide connectivity. That only increases the cost requirements and coordination required to build out a robust network. The technology is innovative, but it likely needs more time to develop and see if it can get past the early adopter phase.

PNK, or Portable Network Kit, is another solution developed by several community organizations as a response to Hurricane Sandy. PNK is an open source project made up of off-the-shelf components that enables a community to build out a wireless network. It ranges from $500-$3000 for the components, depending on your requirements [44]. The kits have the flexibility to be deployed with solar panels or backup batteries and can be meshed together to provide more range or throughput. They have developed instructions and configurations to make deployment easier, so that someone with basic computer skills can deploy and support a kit. The solution has both online and offline functionality. In the event that the network loses connectivity to the internet, it goes into "island" mode that allows users to continue communicating and coordinating in the event of a natural disaster [45]. The groups supporting PNKgo also had a crowd funded response to the disaster in Puerto Rico, deploying two PNKs in San Juan and training five residents to setup and support the network [46].

Several other software based mesh networking projects are attempting to compensate for the lack of connectivity or subvert governmental controls or censoring of the internet. Most of these solutions are open source projects that are attempting to solve the problem with existing hardware. RightMesh is trying to create a decentralized wireless mesh network that utilizes WiFi, Bluetooth or WiFi direct to allow any Android or JAVA enabled device to communicate and the network provides end-to-end encryption [47]. They are trying to build a peer-to-peer network that could route traffic without the traditional infrastructure of the internet. Nodes will also be able to communicate offline in the event that they are disconnected from the internet. RightMesh relies on the Ethereum network to provide a unique identity and the token will allow an economic incentive to provide resources and connectivity as well as a marketplace for the network [47].

RightMesh has potential, but they also have significant challenges. Their ICO raised $30 million USD, with an initial evaluation of $1 USD per token, but now the token price is down 95% from the ICO. The entire crypto market is suffering, resulting in a significant drop in valuation. They are still reliant on the internet providers that they are trying to replace and those providers are likely to clamp down on users re-selling their services. Without the offline capabilities and token-based payments, they are essentially a cellular MNVO without partners. Further, there is a significant amount of development to complete the network and application to provide the value and functionality that would allow them to overcome these obstacles.

Serval Project is an open source project based out of Flinders University in Adelaide, South Australia started by Paul Gardener-Stephen. It utilizes your phone's WiFi connection to create a mesh network to allow you to call, text or share files without traditional cell service [48]. The application was trialed in Nigeria in 2012. From the feedback from that experience, they have continued to improve on the software and built in security protocols. They have also developed a hardware mesh extender to solve some of the battery and distance limitations [49]. One of the typical limitations of software mesh networking is that it requires internet connectivity to install the application initially. In most disasters, you would have lost connectivity or have limited connectivity to install software. Serval attempts to solve this limitation by allowing you to share the installation from a single phone to others. This would enable to you build your network as long as one phone had the app installed previously.

Briar is a little different in that they are creating a resilient secure peer-to-peer network with a focus on privacy. Briar is an open source project that has created an android application that allows users to transmit messages over Bluetooth, WiFI or Tor if connected to the internet [50]. Their goal is to prevent government or corporate censorship, surveillance, internet blackouts and enable communication during natural disaters. Currently you can only transmit messages, but they are planning to add data transfers in the future [50]. One unique feature of Briar is that it requires you meet contacts in person to establish a connection or have a trusted peer facilitate a connection between two existing friends to eliminate the possibility of a man in the middle attack [51].

Mesh networks have a definite niche that the other solutions cannot easily address. They generally do not scale well, especially since they rely on the network effect to propagate to new users. The value of the networks relies on the number of users that are already on the network. Until a network can build up a critical mass of users, it will languish, as the functionality is limited. The decentralized nature of these solutions is one of their strongest features, but it is likely to face pushback from countries that will restrict the usage of the applications.

Community Networks

Community networks have been around almost as long as the internet has been in existence. They are generally utilize open source and develop their own hardware or utilize commodity hardware to avoid vendor lock-in. Operating in areas that are unserved or lack competition between ISPs, these collective groups around the world are collaborating to solve their own problems with connectivity. They also share their knowledge with others by publishing their code, documentation and specifications. We have tried to highlight a wide variety of community networks and the technologies used from LMICs around the world.

Zenzeleni is a co-op run by the Mankosi community in South Africa. The University of West Cape assists Zenzeleni and they worked with tribal authorities to design and deploy the network. They provide voice, data and cell charging services. Residents pay roughly half the price of the traditional telecommunication company costs and all of the money stays in the community [52]. Residents can call for free within the community and Zenzeleni has partnerships and licensing to connect to external networks. The network utilizes Mesh Potatoes, which are low cost access points to provide household connections [53]. They have plans to upgrade to new versions of the Mesh Potatoes, further expand the network to all of the Mankosi villages and add WiFi calls as a functionality in future network upgrades [54].

Rhizomatica is an NGO that assists community based ISPs in rural Mexico. They have built out a network that provides cellular coverage to 16 villages [55]. Similar to Zeneleni, the indigenous communities were permitted to use frequencies that were not assigned to traditional telecommunication companies. Rhizomatica has published its entire codebase and documentation open source so that any community can build and learn from it. For hardware, they publish the entire bill of materials. For example, they used the NuRAN Wireless GSM LiteCell as the base station [56]. Hermes is a project by Rhizomatica that utilizes high frequency radio or HF. HF is a frequency normally used by ham radio operators, but they are using it along with their cellular BTS solution to provide voice and text communications [57]. Hermes is enabling communities to build out a backhaul network without traditional telecommunication or satellite providers.

In 2011, Rhizomatica, along with other partners, formed the Indigenous Community Telecommunications, hereafter TIC AC, a nonprofit organization that works with the government to regulate the indigenous community networks [58]. TIC AC has faced legal challenges from Mexico's telecommunications regulator over frequency space usage [59]. They are now looking at providing satellite based internet and phone services to circumvent traditional telecommunications providers [59].

There are several other examples of successful community networks. In the Americas there is Alter Mundi from Argentina, Ik' ta K'op Collective in Chiapas Mexico, NetWork Bogota in

Colombia and Coolab in Brazil. The Internet Society has a great report on community networks in Africa that goes through the details of establishing a community network in Africa and making is sustainable. They also list over 30 current or past projects across Africa [60].

All of these are great examples of communities working together to solve the last mile when there is not an economic incentive for governments or corporations to invest. These projects do not necessarily scale, but they do not need to. They solve the issues in their local community and share that information with others so that everyone can adapt the solution to their local context.

Offline Networks

It may seem counterintuitive, but there are several solutions for areas that don't have access to traditional infrastructure or cannot afford the costs of connectivity. They are more of a stopgap solution, but they can be especially effective with metered data plans and in community networks or school settings where you can download the information once and access it multiple times for no cost.

Several projects, such as Rachel, Kiwix and Internet-in-a-box, are attempting to fill this gap. They are open source and combine freely available content and educational tools with hardware that makes it easy to setup an offline lab. These solutions have been deployed around the world to address affordability, censorship and lack of educational resources.

The Kiwix project also has an offline reader that works on almost any device, allowing you to download content when you have access to the internet, but read it later. Mozilla has a similar application, Pocket, that enables the same functions. These applications allow people to utilize free or low cost hotspots, but then consume the content whenever they want.

These projects are very useful and we need to continue developing the functionality, but these are temporary solutions as we continue to reduce the number of unconnected individuals. Similar to the disparity in download speeds, the cached version of the internet does not close the digital divide.

Conclusions

As we have shown, there has been amazing progress in connecting the unconnected, but we cannot allow the progress to slow. The technologies exist and are mature enough to solve these issues. What we need are creative solutions and progressive policies along with cooperation and coordination between governments, nonprofits and corporations.

Cellular networks cover the majority of the world's population, yet more than half are left out of the digital revolution. We must continue to address the issues around basic access, but we need to do so with an overall strategy in mind. Governments need to be more progressive and transparent in spectrum allocation as well as investing in infrastructure. The technologies are continuously improving and becoming more affordable, but there are still issues of digital literacy, age and gender equity, as well as the unserved populations outside of our current coverage areas.

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