Computing for Rural Empowerment: Enabled by Last-Mile Telecommunications (Extended Version)

Technical Report, Draft Date: September 30, 2013

Saigopal Thota[1], Avishek Nag[1], Sw. Divyasukhananda[2], Partha Goswami [3], Ashwin Aravindakshan[4], Raymond Rodriguez[5], Biswanath Mukherjee[1], and Somen Nandi[5]
[1]Department of Computer Science, University of California, Davis
[2]Vivekdisha, Ramakrishna Mission Vivekananda University, Belur, India
[3]Computer Informatics Centre, IIT Kharagpur, Kharagpur, India
[4]Graduate School of Management, University of California, Davis
[5]Global HealthShare Initiative, College of Biological Science, University of California, Davis
{sthota, anag, aaravind, rlrodriguez, bmukherjee, snandi}@ucdavis.edu, rkmsadhu@gmail.com

***Abstract*—The goal to increase economic and educational exposure, and to promote global health and wellness, can be achieved through the power of sharing knowledge, technology, and resources. Information and communication technology (ICT) can play a key role in disseminating such knowledge across the world. But a digital gap exists between urban and rural/remote areas, which results in economic and social disparities across regions. Developing last-mile telecommunication technologies for rural/remote areas is a crucial aspect in providing ICT services that can integrate millions of stakeholders in rural/remote areas globally into the digital age, particularly with the advent of cloud computing. This article focuses on the different aspects of providing last-mile rural telecommunication access such as interfering factors, technology options, and deployment trends. This article aims to guide service providers, industry practitioners, and local entrepreneurs with a technology-and-deployment-trend analysis to choose, deploy, and operate suitable rural telecommunication networks depending on the unique features of the rural/remote area. The article discusses important problems to address in rural telecommunication networks. We conclude the article with a strategic overview of observations and opportunities for developing affordable and user-friendly last-mile rural telecommunication networks for knowledge sharing and the overall development of the rural economies.**

I. Introduction

The goal to increase global economic citizenship and educational exposure, and to promote global health and wellness, can be achieved through the power of sharing knowledge, technology and resources. Information and communication technology (ICT) can play a key role in disseminating such knowledge around the world. Telecommunication networks can act as a common platform to rapidly connect stakeholders from science, technology, higher education, healthcare [1], agriculture, private-sector/industry partners, service providers, and governments. However, rural/remote areas are characteristically influenced by factors such as scattered user base, resistance to adopt new technology, and affordability. These result in limited or non-existent access network (or last-mile connectivity) infrastructure and lack of penetration of broadband services in these areas. These factors create a digital divide between urban and rural/remote locations, which result in economic and social disparities across regions and countries. Reducing this gap by developing suitable last-mile telecommunication technologies, however, will provide opportunities to bring millions of stakeholders in the rural/remote areas globally into the digital age. Hereafter, in this article, we use the term rural area to refer to both rural and remote areas.

There is a lot of scope for users in rural areas to exploit today's technologies, such as cloud computing and cloud storage, by using minimal resources at the user site and for very low usage charges. Rural users can use these computing services to develop compelling, innovative, and practical applications suitable for their local area, business activities, etc., to improve their quality of living. Last-mile telecommunication networks play a crucial role in connecting rural users to the cloud.

Therefore, revolutionary technologies and appropriate implementation plans need to be explored for next-generation last-mile rural telecommunication networks, which should be robust, flexible, scalable, affordable, and user friendly. The challenge posed to the World Summit on the Information Society (WSIS) is to harness the potential of ICT to promote the development goals of the Millennium Declaration and overcome the digital divide by connecting villages through ICT technologies [2]. In our opinion, addressing these challenges for different scenarios using a single technological approach has little likelihood of success because there are several factors, such as geography/terrain, infrastructure, motivation/incentives, customer base, and users' economic conditions, that constrain/determine the choice of a network solution. We also believe that isolated effort and investments in one area without integration among multiple areas will likely be unsuccessful and not economical.

Typically, telecommunication networks consist of three major infrastructure categories: (1) access network, (2) metropolitan-area (or regional and transport) network, and (3) core network (see Fig. 1). The access network enables end-users (businesses and residential customers) to connect to the rest of the network, and it typically spans a few kilometers. The network that connects access network to the rest of the network is generally referred to as backhaul/backbone/backend network. It consists of the metropolitan and core network. The metropolitan network spans a metropolitan region, covering distances of a few tens to a few hundreds of kilometers, and it is generally based on synchronous optical network/synchronous digital hierarchy (SONET/SDH) optical ring networks as well as emerging carrier Ethernet technology. A metro-core aggregation ring, as the name suggests, aggregates traffic from multiple metropolitan access networks using aggregation switches and routes the traffic to the core network. The core network provides global connectivity with the help of core routers and switches, and spans long distances such as few hundreds to a few thousands of kilometers. Network operators, service providers, and researchers continue to address challenging issues to evolve the network infrastructure to accommodate higher bandwidth requirements with increasing traffic. But an important challenge yet to be addressed is how to provide cost-effective last-mile connectivity to rural areas.

In this article, we focus on the different aspects of providing last-mile rural access. We analyze the interfering factors that affect rural network deployments, available technology options, deployment trends and case studies, and important open problems. In order to consider all these criteria, an interdisciplinary and integrated approach is necessary for selecting a suitable network solution. Our objectives are to open up the discussion among governments, non-governments organizations, and entrepreneurs; and to provide network solutions to rural areas with sustainable models by reviewing multiple deployment trends and choose the ideal solution for a given specific scenario.

In this article, we also present a detailed economic analysis on the cellphone and Internet penetration with respect to income levels of 50 nations in Section IV. From the analysis we observe that internet penetration today is tightly correlated to the average income levels of people, where as cellphone penetration, on the other hand, is widely observed throughout the world with 96% global penetration. This is a strong example showing how a technology penetrates into a society and people will adopt it, irrespective of their economic status, if it is made affordable and user-friendly with compelling use cases. The goal for providing network connectivity to rural areas should be to make the technology affordable, user-friendly, and to develop compelling applications and use cases. Smartphones, can play a major role in this context as they can provide both cellular and Internet connectivity. Even though smartphones are not yet used widely in rural areas, their penetration will increase in the next few years similar to cellphone adoption in rural areas, especially with their price going down.

We present some important issues that needs to be solved to significantly improve access network solutions with operational and financial sustainability. Finally, a brief strategic overview is provided to capture importance of the complexity of this multidisciplinary problem.

A. Vivekdisha

In this article, we present our deployment activity of a rural telecommunication network to support an education-and-healthcare-service initiative in India called Vivekdisha.

Vivekdisha (http://www.rkmvu.ac.in/content/vivekdisha) is an ICT-based initiative by Ramakrishna Mission Vivekananda University (RKMVU) aimed towards upliftment of rural India using videoconferencing as its backbone, providing online and offline tele-education, tele-medicine services in a manner adapted to local communities for creating a sustainable future in those areas. Vivekdisha has around 18 centers in states of West Bengal and Jharkhand (as of April 2012) providing these services.

RKMVU collaborates with researchers at University of California, Davis for global health information and ICT-infrastructure-development support (http://uoip.ucdavis.edu/newsletters/FE/2013W/GlobalHealthShare.cfm). As part of the case studies, we present our deployment activity to provide connectivity to one of the remote centers of Vivekdisha, in Section V-C.

II. Interfering Factors

There are several factors that are crucial in determining a viable technology solution for setting up last-mile connectivity in rural scenarios. Some such factors are reviewed below.

A. Geographical Location

The geographical location determines the terrain and hence the challenges associated with its characteristics (i.e. flat lands, hilly areas, dense forest areas, etc.). A hilly and densely forested area may have more fading (reduced signal intensity due to the propagation of signal in multiple paths and interfering with each other) and signal power loss (loss in the intensity of the signal power) compared to a relatively flat area with less tree canopy [3]. Location governs the cost associated with the infrastructure development and transportation of telecommunication equipment, troubleshooting and maintenance of the network. In some places, there might be available optical fiber or wired network infrastructure that is used by other organizations (e.g., railway network or a power-line network), or a backhaul connection between two cities which can be used as a backhaul for last-mile access.

B. Economic Conditions

Affordability of a network service by end-users is the ultimate driving force for developing a cost-effective solution. Therefore, low-cost network solutions are required for rural areas in developing nations. Customer density and economic condition of users determines the selection of technology. For example, WiFi operates on unlicensed Industrial, Scientific and Medical (ISM) spectrum band, which is open for usage without a regulatory fee (unlike licensed bands in the spectrum

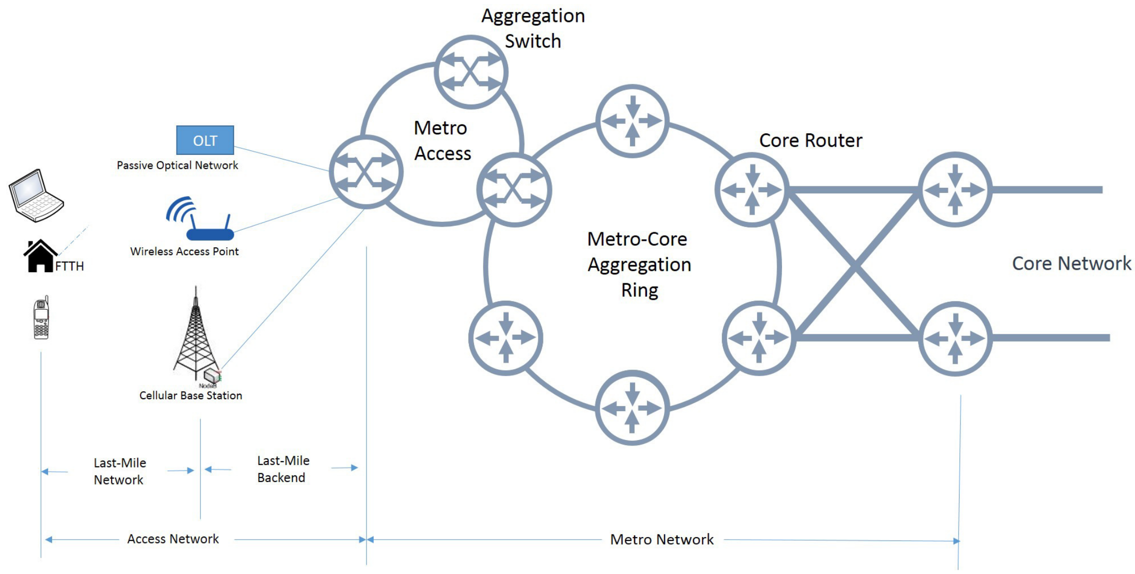

Fig. 1. Major infrastructure categories in a telecommunication network.

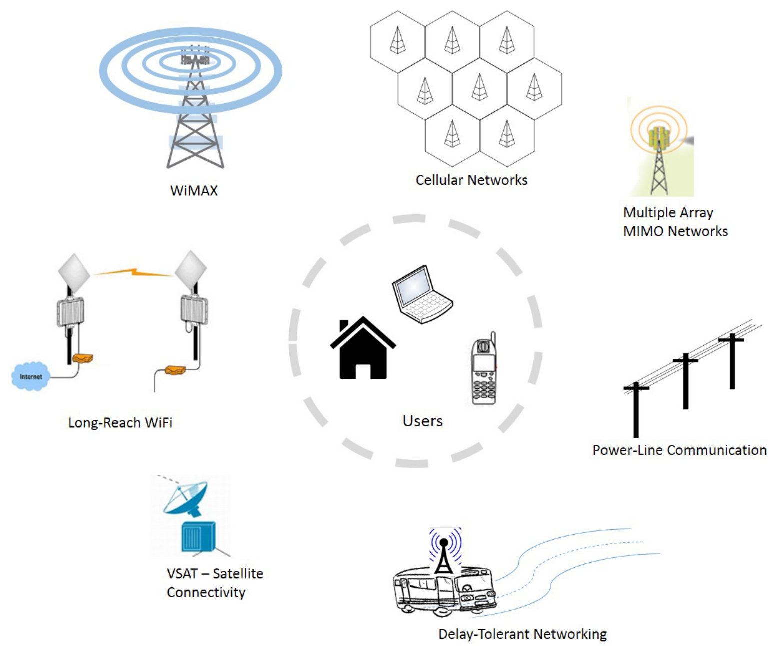

Fig. 2. Technology options and deployment trends for last-mile telecommunication in rural areas.

which are regulated by telecommunication authorities with a spectrum-usage license fee) where as Worldwide Interoperability for Microwave Access (WiMAX) requires licensed spectrum which will be billed to the users indirectly. Therefore, suitable network solution needs to be selected based on the affordability of users with appropriate return-on-investment (RoI) to the service provider.

C. Motivation/Incentives and Adoptability

In developing economies, there are many remote but populated regions with barriers for development such as lack of road infrastructure, which may disconnect the people from the benefits of urban world. Such barriers contribute to knowledge, economic, and social disparities resulting in lack of entrepreneurship and social innovation. Insufficient knowledge among these bottom-of-the-pyramid large-scale customers may lead to ignoring and underestimating the benefit and power of ICT. Community-based participatory research (CBPR) is essential to motivate the end users to become integral partners in this multi-stakeholder value chain. The role of CBPR and the overall dynamics for sustainable intervention has been discussed in similar low income settings in [4] [5]. Upon asking people in some underserved communities how they spend the limited money they save; not always but sometimes, they prioritize spending it on ICT options [6]. Multiple examples can be found (see [4]), where low-income customers have generated incomes around the technologies and by using them [6]. Creating exposure and awareness about the benefits of ICT will enable rural communities to adopt technology solutions. It is important to customize the solution that is culturally and behaviorally acceptable and adaptable. Besides connecting the ultimate stakeholders (users), who are currently beyond the reach of the limits of connectivity to the world of could computing, applications, and services, last-mile networks certainly enable increased self-sufficiency among rural communities.

A single "fit-for-all" solution does not exist for telecommunication in rural areas, and based on different interfering factors presented here, network solutions need to be evaluated and selected for a particular scenario. Some deployment trends based on available technologies along with their pros and cons are summarized in I.

III. Available Technology Options

Various technologies suitable for last-mile broadband network solutions have emerged. The choice of technology depends on user affordability, potential for penetration, data rates, performance of the network, potential-customer base, incentives/profits to the service providers, etc. These factors may not complement each other. Therefore, it is a challenge to determine one single "fit-for-all" last-mile access solution suitable for all scenarios. Different technology options available for last-mile rural access are described below.

A. Wired

Wired technologies include copper or fiber-based telecommunication technologies. They provide higher data rates; and, unlike wireless technologies, they are less susceptible to external factors such as interference, signal loss, line-of-sight requirements, etc. However, they are generally more expensive compared to wireless technologies. Depending on whether there exists a wired infrastructure nearby, deploying last-mile connectivity using Digital Subscriber Line (xDSL) technologies or a Passive Optical Network (PON) with Fiber to the Home/Curb (FTTH/C) is a viable option. In FTTH/C, the access network connectivity is provided using optical fibers until the home or curb, respectively.

B. Cellular

The success of a particular technology depends on its fast adoption in the market. For example, cellphones have a very high penetration rate in countries like India (where about 75% of the total population uses cellphones, of which 37% of them are rural subscribers [7]), etc. In such scenarios, cellular networks, which already have a network footprint in rural areas, is a possible cost-effective solution for last-mile access. Data communication using cellular networks is also maturing as smartphones are becoming increasingly popular and as 2.5G, 3G, and 4G technologies are being deployed worldwide gradually.

C. Fixed Wireless

Fixed wireless broadband refers to technologies where a Customer Premises Equipment (CPE) at a user's site connects to a wireless network. They include very small aperture terminal (VSAT), IEEE 802.11 (WiFi), and IEEE 802.16 (WiMAX) technologies. In VSAT, a small satellite transmitter and receiver with directional antennas, transmitting signals in a particular direction/sector, communicate with VSAT access satellites. VSAT could be a good candidate in setting up broadband links in remote areas. WiFi provides short range communication with speeds of up to 54 Mbps today and throughputs of around 500 Mbps using newer standards under development, such as IEEE 802.11 ac. WiFi can provide reliable communication at very low costs as WiFi devices are inexpensive due to large-scale adoption. Hence, WiFi is a suitable low-cost last-mile access solution. WiMAX (or 4G), on the other hand, has higher coverage range compared to WiFi and can prove to be a good backhaul for WiFi access points [8] and Base Stations (BS) in cellular networks. Free-Space Optics (FSO), which uses infrared communication between a pair of optical transceivers within line of sight, is another mode of fixed wireless communication that has gained attention recently [9].

For providing last-mile broadband in rural areas, most deployments we observe are based on wireless technologies due to the cost-effectiveness, flexibility, and ease of installation, especially in challenging terrains. However, the backhaul connection from the wireless terminal to the core network generally uses wired connectivity (fiber or copper).

Some hybrid architectures are also explored for access networks, where two or more wired/wireless technologies are used in conjunction to exploit the unique features of each technology. A discussion on such hybrid technologies is provided in Section V.

IV. Economic Analysis: CellPhone vs. Internet Penetration

From an analysis of cellphone and Internet penetration go 50 nations with respect to their economy, it is observed that income is a strong indicator of access to the Internet. Almost 80% of the variation in Internet access across nations can be explained by the variation in the income levels (correlation of 0.91, source: World Bank Data Archive (GNI: http://data.worldbank.org/indicator/NY.GNP.PCAP.PP.CD; Population: http://data.worldbank.org/indicator/SP.POP.TOTL; Internet Penetration: http://data.worldbank.org/indicator/IT.NET.USER.P2; Mobile Penetration: http://data.worldbank.org/indicator/IT.CEL.SETS.P2)). Consequently, developing countries lag the developed ones by a significant margin, in terms of access to the Internet. According to the International Telecom Union's (ITU) The World in 2013: ICT Facts and Figures (http://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2013.pdf), only 39% of the global population has access to the Internet - 77% of the developed world and 31% in the developing nations. Furthermore, this variation sustains itself even across and within the developing nations, where higher income (or more

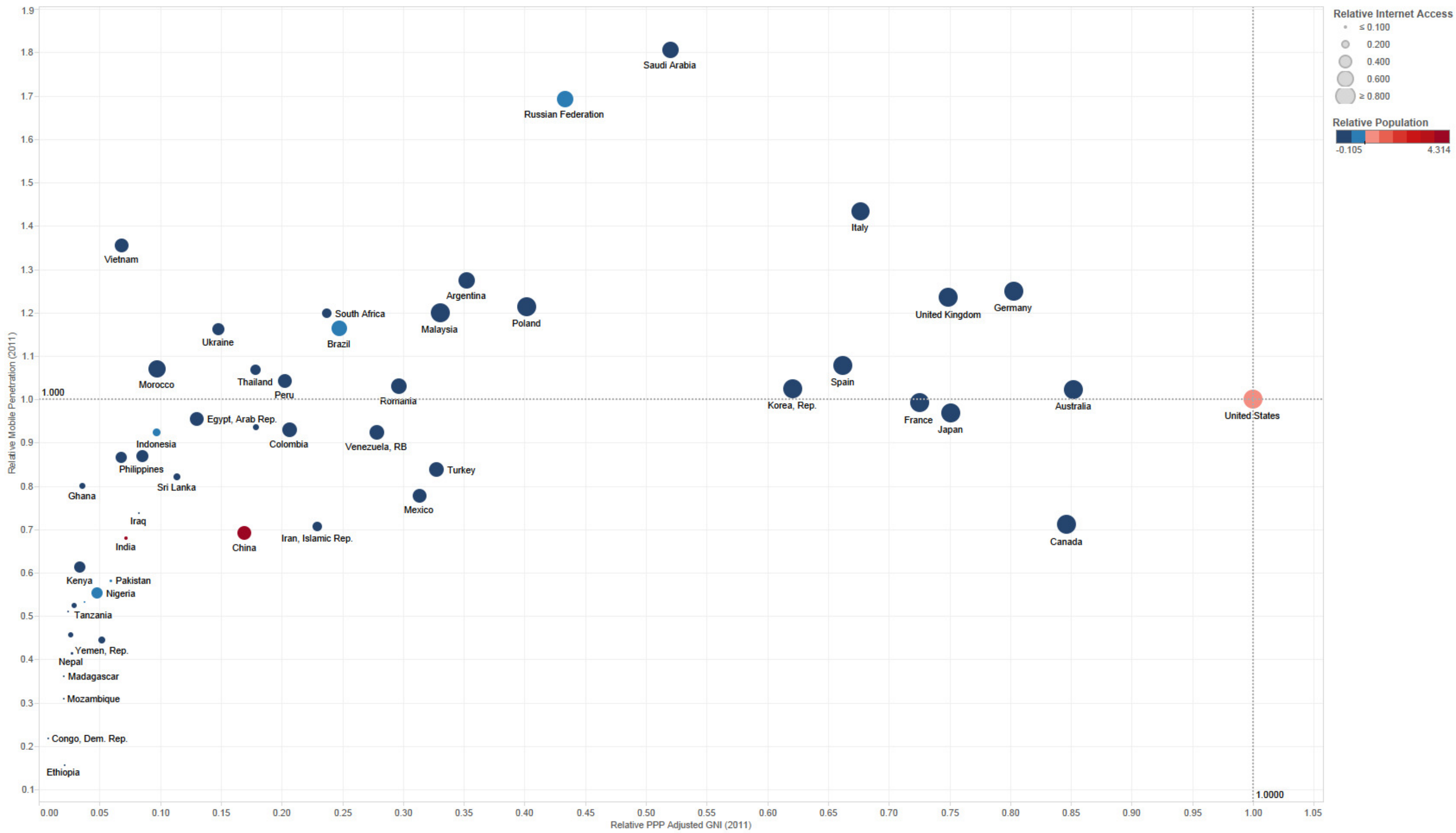

Fig. 3. A schematic representation of cellphone vs. Internet penetration of 50 countries with their Gross National Income (GNI).

TABLE I
DEPLOYMENT TRENDS BASED ON DIFFERENT NETWORK TECHNOLOGIES: PROS AND CONS IN THE CONTEXT OF LAST-MILE RURAL CONNECTIVITY

Deployment Trend/ Technology	Cost		Coverage/ Penetration	Spectrum	NLOS*	Data Rate	Power	Deterioration/ Interference	Remarks
	Infra.	Oper.							
Long-Reach WiFi	Low	Low	Low	Unlic.	No	Low	Low	High	Uses off-the-shelf equipment, hence low-cost
WiMAX based	High	High	High	Lic.	Yes	High	High	Low	User devices do not have WiMAX interfaces, need WiFi last hop
Delay-Tolerant Networks	Low	Low	High	Unlic.	Yes	Low	Low	Low	Delayed response time, not suitable for real-time applications
Hybrid Wired and Wireless	High	Med.	Med.	Unlic.	Yes	High	Low	Med.	Low cost and flexible connectivity
Cellular	High	High	High	Lic.	Yes	Med.	High	Med.	Provides both voice and data communication. Rapidly penetrating technology
Cognitive Radio	High	Low	High	Lic.	Yes	High	Low	High	Can exploit unused licensed spectrum
Power-line Comm.	Med.	Low	High	Unlic.	Yes	High	Low	High	High penetration of power lines come to the advantage
MIMO Wireless	High	Low	High	Both	Yes	High	Low	Low	Expensive
Alternative Telecomm. Networks	Low	Low	High	Both	Yes	High	Low	N/A	Leverage existing infrastructure, not widely available

*NLOS: Non Line of Sight

developed sections) of the nation have relatively better access (e.g., broadband) to the Internet, but economically deprived (and rural) regions tend to be severely restricted. Currently, about two-thirds of the world population are offline and denied access to the world's largest repositories of knowledge and commerce. The reasons often cited for this divide include the high cost of computers, investments in infrastructure to bring connectivity to regions, cost of fixed broadband access, and lack of population density to justify investment, political instability, and regulatory bureaucracy.

In contrast to this, cellphone penetration is ubiquitous. The ITU estimates that cellphone access has reached 96% globally - 128% and 89% in the developed and developing world respectively. Income, though important, explains only about 30% of the variation in cellphone penetration across nations (correlation of 0.56). Using data from the World Bank (2011), we illustrate this contrast in Figure 3. The graph plots internet access (non-mobile), mobile penetration, purchase-power-parity-adjusted gross national income (PPPGNI) and population size for the 50 most populous countries in the world. The data is normalized relative to USA, where USA equals 1 for all the measures. The size of the circle indicates relative Internet access in the nation and the color denotes the relative population size.

It is evident from the data in Figure 3 that several nations that have very low gross income relative to the US also have extremely low levels of Internet access (denoted by sizes of the circles). However, we observe that lower income is not necessarily an indicator of lower mobile penetration as several countries with lower income levels have higher mobile penetration in comparison to the USA. For example, South Africa, which has a lower income level (about 25% of USA), has a lower Internet penetration (between 20-40%), however mobile penetration is 20% higher than USA. The graph thus serves as a clear indicator of the fact that disparity in income does not translate to disparity in cellphone access.

More importantly, this ease of access to cellular networks represents an enormous opportunity to improve Internet access through the mobile device rather than fixed-line providers. Even though smartphone penetration lags the basic phones currently, it is expected that the continued decrease in price of smartphones will increase the number of Internet-enabled devices (from 14% now to about 42% in 2017, CISCO Visual Networking Index, Global Mobile Data Forecast 2012-2017). However, this increase in smartphone usage necessitates heavy investment in 3G (and 4G) infrastructure, which might occur at a slower rate than the adoption. This eventuality could render the benefits of smartphone growth ineffective. One possible avenue to expedite the benefits would be developing WiFi networks that can be used by smartphones for Internet access and also by creating of apps suitable for current network conditions (e.g. apps that can run on 2G network or networks with slow data rates). This encourages smartphone usage on the current infrastructure and allowing for investments in infrastructure improvements to catch up to the adoption rate.

While infrastructure investment remains a critical component of mobile internet penetration, attention is to be paid to innovative, compelling, and practical use cases, applications, and incentives at the local and regional level to encourage Internet and smartphone adoption. Pilot studies have shown multiple benefits of improving mobile access and smartphone use - for example, Safaricom in Kenya developed a mobile payments platform named M-Pesa, where airtime can be used as currency; an Android based mHealth system, implemented in Kenya to monitor and perform clinical care (for about two millions persons) during home visits in resource-constrained environments proved to be a viable and cost-effective solution at scale to collect electronic data during household visits [10]; similarly, a review of smartphone use in medicine and health education found that they provide an enormous opportunity to improve health outcomes [11]. Given the opportunities that exist to expand coverage and use, incentives such as, (a) allowing for more rapid investment in infrastructure, (b) investment in apps that can be used on 2G networks, (c) investments in apps that support foundational functions like informing, training, education, nutrition and healthcare, as well as (d) apps that allow for local adaptations that include culture and language [12] [13] would help improve the utility that people in the developing world would derive from the smartphone and in turn the use of the Internet.

V. Deployment Trends

In Section III, we described various technologies for last-mile connectivity in rural areas. Some deployment trends based on those technologies are summarized below. A summary of different deployment trends with case studies is presented in Table II.

A. Long Reach WiFi

There is a lot of research and deployment activity in setting up long-reach WiFi networks due to the commercialization of WiFi and the availability of low-cost off-the-shelf equipment. Besides, WiFi operates in unlicensed frequency spectrum. Some such deployments are reviewed here.

Long-reach WiFi deployments in India include the Digital Gangetic Plains (DGP) and Ashwini projects where the primary goal is to provide Internet connectivity to remote rural areas. Network planning for setting up long-distance links and performance metrics are defined [14] [15]. In Aswhini, the data rate target per village was 384 kbps to enable high-quality video conferencing. Carrier Sense Multiple Access, Collision Avoidance (CSMA/CA) is not a suitable Medium Access Control (MAC) protocol as there is no contention between multiple links unlike regular WiFi deployments. The longest link established in DGP is about 39 km.

Deploying WiFi-based long-distance networks is explored in [16] with links as long as 50-100 km. Real-world deployments give poor end-to-end performance as the 802.11 MAC protocol is developed for short-range communication. To overcome the shortcomings of WiFi over long distances, essential changes are proposed such as adaptive loss-recovery mechanism (showing 2-5 fold improvement in Transmission Control Protocol (TCP)/ User Datagram Protocol (UDP) throughput) and Time-Division Multiple Access (TDMA) on frequency bands with high signal loss during transmission.

In a different work, a testbed is deployed to measure the performance of very-long-distance single WiFi links in two cases - Merida to El Baul (279 km) and El Aguila to Platillon (382 km) [3]. For such extreme long distances, an unobstructed line-of-sight and at least 60% of first Fresnel zone are required. A detailed account on the constraints, choice of locations, and deployment experiences is provided. The data rates were around 65 kbps with unmodified IEEE 802.11 protocol. By modifying the 802.11 MAC protocol from CSMA to TDMA (as in [16]), the achieved throughput increased to 600 kbps, allowing video transmissions.

In [17], a multi-hop long-range WiFi network is proposed with relay nodes between the end-user terminal and a rural telecenter. The WiFi relay points are solar powered, self-sustainable units with their own omnidirectional antenna module, which transmits signals in all directions uniformly. The nature of the power consumption of the equipment has been studied and optimized to suit the solar power supply system and vice versa. This architecture is self-sustainable as well as cost-effective. The WiFi relay point locations were chosen based on the antenna range, maximum accessibility, and the Fresnel zone clearance level between the relays, as this is crucial in providing uninterrupted wireless connectivity, particularly with very-long-distance links.

B. Cellular Networks

The penetration of cellular phones is increasing rapidly. Tele-density in rural areas is also significant in most countries and hence cellular network can be an efficient last-mile connectivity solution for rural areas. They have the advantage of providing voice as well as data connectivity which can enable multiple application services, particularly with the advent of cloud computing. In [35], a healthcare delivery model is proposed where a mobile handheld device is used as an information transmission tool instead of a personal computer. The mobile device communicates healthcare data from a rural patient to a centrally located healthcare provider.

But in rural areas, due to low volume and density of potential subscribers, large telecom operators are not interested to deploy cellular infrastructure and provide services. Financial constraints with small purchasing power in rural areas lead to a cost-demand mismatch to cover the high capital and operational expenditure. So, there is a limited or no cellular coverage in these areas. Rural regions also lack stable grid-based power sources to support large telecommunication infrastructure.

The lack of infrastructure is pronounced in Sub-Saharan Africa, making current-day cellular-connectivity approaches challenging to deploy. Unlike majority of african villages, Villages Macha and Dwesa host local wireless networks through satellite gateways. Cellphones are more prevalent and easier to use than PCs. Therefore, a cost-effective Global System for Mobile Communication (GSM) cellular network called VillageCell, is developed to provide localized cellular coverage [18]. It operates in conjunction with an existing local rural area network. VillageCell uses a software-defined-radio (SDR)-controlled software implementation of the GSM stack, called openBTS. OpenBTS transmits and receives signals in GSM bands and serves as local cellular base station, providing core cellular services for a fraction of the cost of a commercial base station. Multiple base stations are connected through the local wireless network and calls are routed via private branch exchange (PBX) servers implemented in an open source framework, called Asterisk (www.asterisk.org).

TABLE II

SUMMARY OF DEPLOYMENT TRENDS WITH CASE STUDIES ON LAST-MILE TELECOMMUNICATION IN RURAL AREAS

Last Mile Technology	Access Backend	Article	Antenna	Remarks
WiFi	WiFi	B. Raman, et al. [14] [15]	Directional	Long-distance multi-hop WiFi links as backhaul for connecting multiple villages
		R. Patra, et al. [16]	Directional	Long-distance WiFi links with adaptive loss recovery mechanism showing improvements in TCP/UDP throughput and TDMA.
		R. Flickinger, et al. [3]	Directional	Very-long-distance links tested with end points on hilly areas for line-of-sight. Link distances of unto 382 km.
		K. Ab-Hamid [17]	Directional	Multi-hop network with relays powered by solar, making network self-sustainable in hilly terrain.
Cellular	Satellite	A. Anand et al. [18]	OpenBTS Implementation for GSM	VOIP-based calling as using cellphones is easier than PCs in hilly areas.
Cellular	WiFi	A. Dhanunjay, et al. [19]	OpenBTS-based GSM micro cells and wireless mesh	Providing Internet and cellular voice services using solar-powered low-power microcells
		J. Fitzpatrick [20]	Femtocells	In case of low-user density, femto cells are a good alternative to provide cellular connectivity with a long-distance WiFi backhaul.
Cellular	Any	F. Simba, et al. [21]	3G Omnidirectional	Discusses advantages of UMTS 900 MHz for lower path loss and higher coverage at the expense of lower bandwidth.
WiMAX	Satellite	I. Siebrger, et al. [22]	WiMAX local loop	WiMAX local loop created using Alvarion BreezeMAX technology and is connected to the Internet using VSAT.
WiFi	WiMAX	P. Goswami, et al. [23]	Omnidirectional WiMAX base station	WiMAX base station provides blanket coverage, and outdoor CPEs are used to connect to the base station and WiFi for local access.
		D. Chieng, et al. [8]	Omnidirectional WiMAX base station	Multi-tier multi-hop WiMAX and WiFi backhaul and WiFi access tiers with a WiMAX base station serving multiple hexagonal cells with WiFi routers.
WiFi	Moving vehicles	A. A. Hasson [24]	Mobile Access Points	Requests queried are stored and forwarded using public transport vehicles. Data transferred from an area with Internet connectivity through vehicles.
		S. Issacman, et al. [25]	Mobile Access Points	Similar to above, but uses low-bandwidth cellular data for sending user-queries to reduce response time.
WiFi	Optical Fiber	S. Sarkar, et al. [26]	Omnidirectional mesh	Combines the high-speed connectivity of fiber and flexibility and cost-effectiveness of wireless.
TVWS	Cellular	A. Achtzehn [27]	Cellular omnidirectional antenna	Uses TVWS for greater cellular bandwidth on existing cellular towers.
TVWS	Any	C. McGuire, et al. [28]	Omnidirectional	Leverages greater coverage area of spectrum in TVWS to provide blanket coverage.
Power lines	Power lines	A. M. M. Altrad, et al. [29]	Not Applicable	Uses existing power-line distribution infrastructure to homes to provide network connectivity.
Wireless (WiFi)	Power Lines	D. Fink, et al. [30]	WiFi access points	Data communication ove power lines to users' homes
		A. M. Sarafi, et al. [31]		Wireless-Broadband over Power Lines (W-BPL) use Medium Voltage power lines as backhaul and wireless antennas for user-access.
		I. K. Vlachos [32]		Proposed system shows performances of raw 200 Mbps after management data requirements such as smart grid applications.
MU-MIMO	Cellular	I. Latif [33]	Sectorial	Presents testbed LTE measurements with 800 MHz using multiple antennas to improve throughput and minimize interference.
		N. L. Ratnayake [34]	Sectorial	TV Analog spectrum in Australia for sparsely-populated areas leveraging spatial multiplexing gain.

The system allows free calls within the local network and standard connections to outside callers using the satellite link. VillageCell uses free, open-source solutions and off-the-shelf hardware, and hence the total deployment cost is minimal and the solution is scalable.

Mobile operators generally rely on T1, copper, optical fiber, or microwave links for backhauling connections from base stations. Alternate backhaul solution such as a point-to-point WIFI can be used as backhaul as a much lower-cost alternative than traditional microwave (both for infrastructure and licensing) using off-the-shelf equipment and unmodified drivers for rural areas with lower bandwidth requirements.

WIRE is a low-cost, low-power network that extends data and voice connectivity from closest town/city using openBTS based GSM microcells and wireless mesh to provide cellular and Internet services within rural regions [19]. The power required by microcells is low and hence they are solar powered. The backhaul connection to the micro base station is the long-distance wireless connection as proposed in WiLD [16]. Similar to the deployment discussed above, the voice and data from users are forwarded to the open-source Asterisk PBX system, and the users use their existing cellphones for communication.

Another solution proposed for cellular connectivity in sparse rural ares is to use a small, low-power cellular base station, called femtocell, which connects to a broadband network and provides cellular connectivity within its coverage range [20]. Current day femtocells can support 16-64 simultaneous calls covering a radius of 1.5 km. In rural areas, providing cellular connectivity with femto cells reduces the cost from $200,000 (for a macrocell, i.e., a traditional cellular base station) to $100 (for a femtocell). In [20], a numerical analysis of the capacity of long-reach-WiFi backhaul to support femtocells is performed and the results show that a large number of simultaneous, high-quality voice calls can be supported with the proposed solution.

Cellular networks in developing nations, especially in rural areas, are deployed mostly to serve voice traffic. Providing data services over cellular networks in rural areas is more challenging.

There is a rapid evolution of mobile wireless technologies; 3G and 4G technologies can offer broadband capacity. Widely-deployed 3G systems are implemented at 2100 MHz, which incurs high signal loss and smaller coverage suitable for densely-populated urban areas. Data coverage using 3G in rural areas can be addressed by using a lower frequency band such as the emerging 900 MHz technology which incurs lower loss and higher coverage at the cost of lower bandwidth. There are multiple worldwide commercial deployments of 3G networks at 900 MHz. The work in [21] presents radio network dimensioning and techno-economic analysis using Tanzania as a case study, where lesser number of sites and base stations as well as Radio Network Controllers (RNC, which carry out radio resource management in cellular networks) are sufficient while using 900 MHz compared to 2100 MHz. Universal Mobile Telecommunications System (UMTS) 900 has an acceptable Internal Rate of Return (IRR) and cost analysis show that capital and operational expenditure of UMTS 900 is cheaper and helps in realizing the cost-demand scenario for rural deployment.

Fig. 4. A Vivekdisha's education and healthcare center equipped with our WiMAX-based last-mile telecommunication solution. Figure on the right shows the mast used to host the WiMAX CPE and figure in inset shows the WiMAX CPE that connects to the base station [23].

Another work on rural cellular connectivity proposed the use of Internet enabled mobile phones as a back-channel to provide temporary internet connectivity in disconnected areas by opportunistic aggregation of cellular data uplink capacity from multiple mobile phones [36].

C. WiMAX based solutions

WiMAX-based network solutions are important to consider for last-mile connectivity in rural areas as WiMAX has greater coverage, supports broadband applications, and can work line-of-sight (LOS) and non-line-of-sight (NLOS). WiMAX can adapt its modulation to provide best data rates and can be operated in a Time-Division Duplexing (TDD) fashion, where upstream and downstream transmissions between a user and a WiMAX base station time-share a frequency band. Therefore, it is more suitable for providing asymmetric data access (i.e., unequal upstream and downstream data rates). In places where no infrastructure exists, WiMAX is a cheaper and faster way of getting a large area covered and therefore a potential "greenfield" solution.

We proposed and deployed a network infrastructure to provide education and healthcare services in India in an initiative called Vivekdisha, where WiMAX base stations provide blanket network coverage in rural areas, and outdoor CPEs are used to connect to the WiMAX base station and to the Internet (see Fig. 4) [23]. We observed that video conferencing and related applications can be provided in rural areas for low cost with bandwidths as low as 301 kbps.

WiMAX based solutions are suitable for rural areas where several places are to be connected around a special location so that point-to-multipoint (P2MP) topology can be used with TDMA to avoid collisions [37].

A WiMAX network deployment is done in Siyakhula living lab, a joint venture between Rhodes university and University of Fort Hare, for introducing ICT in rural areas which is home for 42.5% of the population of South Africa while fixed-line density in some rural areas is less than 5% [22]. A local-loop access network is developed using WiMAX. The work provides the configuration of local Distributed Access Nodes (DAN) (client systems running Ubuntu) placed in schools. A wireless access point at each DAN provides access to users around. Alvarion BreezeMAX technology is used for WiMAX deployment with 256 OFDM carriers. A WiMAX micro base station is housed at Ngwane school, as it is the highest point. The DANs connect to the Internet through the base station over a VSAT connection provided by Telkom, a telecommunications provider in South Africa.

A hybrid access network with WiMAX and WiFi with VSAT backhaul is explored for the case of rural Tanzania where there is no alternative backhaul options [38] [39].

Attributing to the long-reach feature of WiMAX, a hybrid last-mile deployment option is proposed where WiMAX is used as a backhaul option with WiFi routers serving users [8]. In this work, a multi-hop, multi-tier WiFi and WiMAX hybrid network architecture is proposed where there exists a WiMAX backhaul tier, a WiFi backhaul tier, and a WiFi access tier. The deployment provides blanket coverage with a central WiMAX base station serving WiFi base stations (routers) with multiple radios. WiFi routers offer WiFi access or act as multi-hop-relays for other routers or both. The WiMAX base station is connected by a wired backhaul.

D. Delay Tolerant Networking (DTN)

Low-cost connectivity alternatives such as store-and-forward networking are suitable for rural areas with minimum or no existing network infrastructure and where basic data communication is more important than time sensitivity. Applications, such as browsing, can be delay tolerant, where the response to a data request/query (e.g., information, documents, videos, e-mail, etc) will be received few hours after the query is submitted.

One such network solution is deployed in a rural area with about 1000 customers where WiFi access points are setup and the other end of the WiFi connection is in moving public transport vehicles which frequently shuttle between an urban area to the rural areas [24]. WiFi access points cache data requests (queries) made by users and these vehicles collect queries from access points within the range of the traveled routes. The queries are sent to and relevant content is downloaded from the Internet when the vehicles are within range of Internet-enabled hotspots (coverage areas of wireless access points with Internet connectivity) in the urban area. This technology is inexpensive with approximate costs of $0.03 per capita, and it has been successfully tested for rural connectivity in Cambodia and India. But these networks may incur a large response time (time between the query submission and receiving the response) dictated by the frequency of the moving vehicles.

To reduce the response time, a hybrid DTN solution is proposed for regions with cellular connectivity [25], where mobile devices are coupled with delay-tolerant networking to provide Internet access with reduced response time. This is achieved by combining high-bandwidth but high latency DTN with low-bandwidth, low-latency, and relatively expensive cellular data connectivity (General Packet Radio Service (GPRS), etc.). Page requests from the rural area are sent via cellular links, and the replies are sent via DTN using the frequent public transport vehicles. This hybrid network perform 33% faster than a DTN with the additional cellular-data expense tradeoff.

E. Hybrid: Wireless and Wired Networks

Hybrid wired and wireless broadband access technologies are becoming popular as a last-mile access solution. These technologies achieve the best of both worlds with the speed, Quality of Service (QoS), and robustness of wired technologies, and the flexibility and low cost of the wireless frontend. In [26], a hybrid wireless-optical broadband access technology is reported with a wireless mesh network at the frontend and an optical fiber based backend. The deployment of hybrid WiFi with wired backhaul is reported in [40] and [41]. This technology is cost effective if the wired infrastructure already exists and can be accessed within the reach of the WiFi frontend of the access network.

F. Cognitive Usage of Unutilized Television Spectrum

Cognitive-radio technology enables utilization of unused licensed spectrum by sensing the environment and adapting accordingly. The IEEE 802.22 wireless regional area network (WRAN) standard is based on time-division duplexing (TDD), orthogonal frequency division multiple access (OFDMA), and opportunistic use of very high frequency/ultra high frequency (VHF/UHF) TV bands [42], referred to as TV whitespaces (TVWS). In different works, techniques and deployment scenarios are presented for cognitively using these unutilized television bands for last-mile rural connectivity.

TV whitespace(TVWS) have received renewed attention after the 2010 FCC ruling on the opening of these bands for secondary systems. Reference [27] discusses a cognitive-radio deployment in southern Rhineland, Germany where cellular operators are the secondary users using their existing cell sites for secondary transceivers. This improves the network capacity without significant capital expenditure. The work explores frequency planning and the distribution of secondary users.

TVWS-based last-mile access is suitable to provide wireless broadband access to rural and suburban areas with an average coverage radius of 33 km (and up to 100 km). Large network coverage and availability of whitespaces in the spectrum make this technology particularly suitable for rural deployment. The cost-demand mismatch in rural areas for network connectivity is solved due to free usage of licensed spectrum and large coverage.

A wireless broadband access network, called Hopscotch was deployed on the west coast of Scotland where Point-to-point (P2P) and Point-to-multi-point (P2MP) links similar to WiFi but using whitespaces in UHF are used to provide network coverage [28]. The advantage of using UHF is wider coverage and non-LOS links. P2P links are used for backhaul and P2MP links are used for providing blanket coverage. WiFi in 5 GHz is used to serve subscribers in close vicinity. The combination of spectrum bands allows tradeoff between throughput and coverage with high throughput and shorter range in WiFi vs. greater base station coverage (almost 4 times) at reduced channel bandwidth and throughput using TVWS (especially in challenging terrains). The combination of 5 GHz WiFi and UHF bands reduce the burden on base-station coverage and transmit power requirements. Substantial reduction in path loss and improved throughputs are observed at UHF frequencies compared to 5 GHz especially in longer non-LOS links.

Another deployment using cognitive radio as the last-mile technology is setup in Malaysia's community broadcast centers, which are connected by wired connection or VSAT. VHF and UHF are suitable spectrum for last-mile access to leverage the low spectrum occupation and hardware costs. Basic architecture includes base stations and CPEs, where base stations do cognitive sensing, and decides which frequency to use. This paper gives some results on the feasibility of the co-existence of WRAN base stations and DVB-T base stations [43].

G. Power-Line Communication (PLC)

PLC is another solution for broadband access known as the "third wire". PLC enables utility companies to deploy communication networks over existing power-line infrastructure by transmitting data signals through power cables that transmit electricity. Electromagnetic waves carry information-bearing signals via the Medium Voltage (MV) and Low Voltage (LV) lines, together with electric power. High-speed transmission of data, voice, video, etc., via power cables would be invaluable for rural areas as the electricity infrastructure reaches most rural areas, thereby reducing the telecommunication capital expenditure. A PLC model for broadband over power lines with MV or LV nodes converting IP-based communication signal to other suitable signal for transmission through power lines is proposed in [29]. The work proposes using power-line network as Ethernet carrier and presents a mathematical model showing effect of distance.

A company, Xeline, conducted trials with a Korean electricity company with data rates of 2 Mbps. In the access segment, PLC uses LV distribution lines to provide access to houses or offices, connecting backhaul to customer and in-building home-wiring network to distribute the signal giving data rates up to 14 Mbps.

Medium voltage at 7200 V is mentioned as the most important configuration at the metro-level distribution to assure cost-effectiveness and for timely market roll-out compared to traditional backhaul alternatives such as fiber optics, etc. A field test provided throughput of 45 Mbps (27 downstream and 18 upstream) over a distance of 600 m using repeaters to assure the signal through distances.

A hybrid architecture using MV lines and wireless (to replace LV in the access) is proposed where the MV lines act as as backhaul links, and the last-hop of the network distribution is done using WiFi/WiMAX wireless access points [30].

A detailed scheme of using the power-line network as an alternate infrastructure suitable for rural areas offering smart-grid applications and broadband access along a 107-km MV power grid in Larissa, a rural area in central Greece is described in [31]. This technology is called hybrid wireless-broadband over power lines (W-BPL). In Reference [32], a broadband network is deployed over two overhead MV lines namely P240 and P250 of total length of approximately 100 km. The system shows performances of raw 200 Mbps after management-data requirements such as smart-grid applications and the remaining bandwidth is available for additional services applications.

H. Multiple Input Multiple Output (MIMO) Wireless Networks

Spectral efficiency of standard technologies such as Wireless Local Area Network (WLAN), Wireless Local Loop (WLL), and WRAN is limited to 6 bits/Hz/cell. To achieve a better spectral efficiency, a broad frequency spectrum or Multi-User Multiple Input, Multiple Output (MU-MIMO) technology is required. In case of APs equipped with multiple antennas, the spectral efficiency and hence the capacity improves linearly as a function of the number of antennas without increasing total transmission power (spatial multiplexing gain) [44].

3GPP UMTS Long-term Evolution (LTE) standard is deployed on top of existing High-Speed Packet Access (HSPA) and HSPA+ networks at frequency of 2.6 GHz to satisfy spectrum demands of densely-populated areas. In the long run, operators are pursuing the idea of LTE for rural areas at 800 Mhz using the recently-freed analog TV spectrum [33]. This work presents testbed LTE measurements in 800 MHz using eurocom's open air interface which is a 3 sector, dual RF, high-power eNodeB, calculated best achievable throughput, and the maximum range of cells. It shows the advantages of opportunistic MU-MIMO.

Providing wireless broadband connectivity to Australia's rural areas is challenging due to a scattered population (2.7 person per sqkm). A novel approach is proposed to use Analog TV spectrum with MIMO to leverage the spatial multiplexing gain i.e., the linear increase in capacity offered by MIMO channels without additional power or bandwidth [34].

In MUSA-MIMO, faster broadband services are provided by employing multiple antennas while user devices have single antenna with wider bandwidth to each user and hence faster data rates. These systems incur low interference and increased range due to beam forcing (a signal-processing technique to reduce signal attenuation with distance) gain at the base station. This work presents details on designing optimum antenna arrays for APs, methods to obtain accurate channel information, effects of weather condition on received signal, etc.

I. Use of Alternate Infrastructure

In many countries, there exists a substantial amount of alternative telecommunication infrastructure. For example, Indian Rail (RailTel), Gas Association of India Ltd. (GAILTel), and the national electricity distribution network (PowerGrid) have their own telecommunication networks. These Alternative Telecommunications Networks (ATNs) operate their in-house communication in their own rights-of-way. They have substantial built-in available capacity and while deploying last-mile connectivity in rural areas, most of these ATN infrastructure can be used in coalition with low-cost wireless solutions. There have been deployments using alternative networks in India as reported in [45].

J. Other Methods

Viabilities of using other methods such as Free-Space Optics (FSO) are reported in Bangladesh [9]. FSO has the speed of fiber with the flexibility of wireless where a data/telecom signal is converted to digital format and transmitted through free space using an infrared carrier. There are many factors that affect the performance of FSO that needs to be studied and considered for deploying such solutions. FSO is free from licensing, translating to low cost of deployment.

Even though Zigbee (802.15.4) has been developed for embedded wireless sensing application senario, the authors in [46] experimented on using zigbee for low-cost voice-based applications in rural areas with low power consumption. Zigbee based voice calling for local network and making use of cellular infrastructure is also explored [47].

VI. Open Problems

Provisioning last-mile connectivity in rural areas has multiple practical challenges and scope for improvement which need intervention from the research community and industry practitioners. We summarize some of them below.

A. Smartphones as Network Devices

The fast market adoption of cellphones needs to be leveraged to provide telecommunication services to rural areas. More people are comfortable using cellular phones compared to PCs. Hence, solutions where cellphone is the user device may be more adopted in rural areas, making it a potential technology option for rural areas. In some of the developing countries, smartphones are not yet as popular in rural areas as in urban markets. But considering the success of the cellphones, it is likely that smartphone adoption will spread out more in the rural sector.

A smartphone, generally, is equipped with WiFi interface using which it can access the Internet through an access point with lower cost compared to cellular data. Most of the work we reviewed in SectionV have WiFi access points for user access. A phone with data connectivity and certain basic features can deliver useful services, including a suitable interface for cloud computing. For example, in [48] a smartphone based ad-hoc network is proposed to deliver emergency healthcare services. Research and development need to be done to design and develop a low-cost rural local loop to provide blanket coverage in rural areas. More research is required to utilize the potential of smartphones by developing compelling and practical mobile applications for rural users.

B. Leveraging Existing Infrastructure

Any existing infrastructure needs to be explored to provide low-cost telecommunication in rural areas. This can range from solutions utilizing telephone/electricity poles to mount WiFi/WiMAX or other antennas to act as relays/access points, to using solutions such as power-line communications.

Sometimes, an optical fiber network connecting two urban areas (cities) can be used to provide connectivity in villages between them with the help of multiplexers and gateway devices. Methods and technologies to efficiently tap bandwidth from existing networks to connect rural areas without jeopardizing the primary connections need to be explored.

C. Reliable Connectivity

Providing infrastructure for end-to-end connectivity in the rural last-mile is not sufficient for proper operation of networks. Mechanisms need to be developed to make the network connection reliable and failure-reselient, offering guaranteed bandwidth especially for delay-intolerant services such as e-learning, health applications, emergency services, etc. Different external factors that affect the performance and consistency of network connectivity need to be identified and analyzed, and network technologies and solutions that are tolerant and independent of these external factors need to be explored.

D. Autonomous Network with Business Models

Rural areas are typically characterized by lack of skilled personnel, sparse population distribution, difficult terrains for transporting equipment, for maintenance and troubleshooting of the network, limited resources such as fuel, electricity, and the users' ability to pay. A common observation is that rural networks are not managed or maintained after the research group which setup the network leaves the site. In some cases, the projects are discontinued due to lack of funds to run the infrastructure.

To prevent such incidents/disruptions, last-mile rural telecommunication networks need to be designed and deployed to be autonomous, i.e., rural networks should require minimal human intervention or should have options for remote management. These networks should have low cost of operation with minimal dependence on external resources such as continuous grid electricity (electric power produced and distributed from a distant thermal/hydro/other generating stations), etc. The fewer the dependencies, the easier the deployment, and the higher will be the adoption of such networks in rural areas. Such networks must also operate with a self-sustaining funding model. The model should provide incentives for service providers and local entrepreneurs to have financial and operational self sufficiency, thus opening up opportunities for rapid penetration in rural areas. Activating demand requires a good value proposition, which involve more than just economic benefits. Hybrid models such as, contiguous, distance, replication, and transfer and translation models have generated some successful business in low income setting, as described in [49]. To create an effective framework for scaling innovation, important factors to consider are cost, active demand, business models, demonstrated outcomes, and effective leadership or execution.

Attractive business models to be owned and managed by local entrepreneurs need to be developed to keep the network sustainable by delivering strong returns on invested capital (e.g. Manila Water, globe Telecom, Smart Communication, etc.). The entrepreneurs will be then responsible to manage the network and troubleshoot it in case of any issues [4]. Hence, next generation last-mile rural networks designers and researchers should develop architectures with focus on both technological autonomy as well as strong business models for financial autonomy for sustainability. In addition to the network infrastructure, the proposed solutions should enable users to exploit the information and computing resources provided by the cloud computing. Cloud computing opens up scope for developing compelling application services suitable for rural areas and can empower the communities with access to information and knowledge and improve their livelihoods. By tapping in to local networks (as discussed in Section II-C), even small companies can profitably serve and bring significant value to low-income customers and shareholders while creating the essential market for economic development of customers at the bottom of the pyramid.

VII. Strategic Overview

The economic, social, and political life in the 21st century is increasingly becoming digital. It is important to provide network connectivity and ICT services to underserved/remote communities to create sustainable growth and to provide improved quality of life. We have identified several factors that significantly affect the design and implementation of last-mile telecommunication networks for rural areas. The deployment trends and case studies from different parts of the world show that one size does not fit all. We strongly emphasize on possible areas of improvement for the research and industry community to develop innovative hardware, software, and sustainable economic/business models that can improve telecommunication in rural areas.

Some important take-away messages perceived from the analysis of case studies and deployment trends are presented as follows. The choice of the technology is crucial in setting up a network solution, and any existing infrastructure needs to be leveraged. This will minimize the infrastructure cost significantly, particularly where public and private sector has limited incentive to create telecommunication solutions in rural areas. Network solutions need to provide reliable and consistent connectivity with minimum guarantees on the quality of service, to grow a healthy and sustaining customer base. This will require the network solutions to be resilient to external factors that affect the consistency and performance of the connectivity. User-density analysis needs to be conducted to identify locations of potential customers to motivate service providers for providing network services. The network solution and the business models need to be autonomous, and operationally and financially self-sufficient for rapid penetration in rural areas, and for them to sustain long after being deployed. Besides providing telecommunication solutions, compelling applications suitable for rural communities that can exploit the compute and data resources of today's cloud computing and networking paradigms such as software-defined networking (SDN) need to be developed to motivate users to adopt and utilize the resources available.

References

[1] S. Surana, R. Patra, S. Nedevschi, and E. Brewer, "Deploying a Rural Wireless Telemedicine System: Experiences in Sustainability," *IEEE Computer*, vol. 41, no. 6, pp. 48–56, June 2008.

[2] "WSIS Forum 2012: Outcomes Document," *http://groups.itu.int/wsis-forum2012/Highlights/OutcomeDocument.aspx*, accessed Apr. 2013.

[3] R. Flickenger, S. Okay, E. Pietrosemoli, M. Zennaro, and C. Fonda, "Very Long Distance Wi-Fi Networks," in *Proc. 2nd ACM SIGCOMM Workshop on Networked Systems for Developing Regions*, 2008.

[4] C. P. Beshouri, "A grassroots approach to emerging-market consumers," *McKinsey Quarterly*, vol. 4, 2006.

[5] C. K. Prahalad and A. Hammond, "Serving the world's poor, profitably," *Harvard business review*, vol. 80, no. 9, pp. 48–59, Sept. 2002.

[6] R. Heeks, "ICT4D 2.0: The Next Phase of Applying ICT for International Development," *IEEE Computer*, vol. 41, no. 6, pp. 26–33, June 2008.

[7] "Telecom Regulatory Authority of India: Press Release No.191/2012," *http://trai.gov.in/WriteReadData/PressRealease/Document/PR-TSD-Aug12.pdf*, accessed Apr. 2013.

[8] D. Chieng, A. Ting, K. H. Kwong, M. Abbas, and I. Andonovic, "Scalability Analysis of Multi-tier Hybrid WiMAX-WiFi Multi-hop Network," in *Proc. IEEE GLOBECOM*, 2011.

[9] N. Saquib, M. S. R. Sakib, A. Saha, and M. Hussain, "Free space optical connectivity for last mile solution in Bangladesh," in *Proc. 2nd International Conference on Education Technology and Computer*, 2010.

[10] Z. A. Rajput, S. Mbugua, D. Amadi, V. Chepngeno, J. J. Saleem, Y. Anokwa, C. Hartung, G. Borriello, B. W. Mamlin, S. K. Ndege, and M. C. Were, "Evaluation of an Android-based mHealth system for population surveillance in developing countries," *Journal of the American Medical Informatics Association*, vol. 19, no. 4, pp. 655–659, Feb. 2012.

[11] E. Ozdalga, A. Ozdalga, and N. Ahuja, "The smartphone in medicine: A review of current and potential use among physicians and students," *Journal of Medical Internet Research*, vol. 14, no. 5, Sept. 2012.

[12] M. J. Rotheram-Borus, M. Tomlinson, D. Swendeman, A. Lee, and E. Jones, "Standardized Functions for Smartphone Applications: Examples from Maternal and Child Health," *International Journal of Telemedicine and Applications*, Sept. 2012.

[13] M. Tomlinson, M. J. Rotheram-Borus, L. Swartz, and A. C. Tsai, "Scaling Up mHealth: Where Is the Evidence?," *PLoS medicine*, vol. 10, no. 2, Feb. 2013.

[14] B. Raman and K. Chebrolu, "Experiences in using WiFi for rural internet in India," *IEEE Communications Magazine*, vol. 45, no. 1, pp. 104–110, Jan. 2007.

[15] B. Raman, "Digital Gangetic Plains (DGP): 802.11-based Low-Cost Networking for Rural Areas 2001-2004: A Report," *http://www.cse.iitk.ac.in/users/braman/papers/dgp-report.pdf*, accessed Apr. 2013.

[16] R. Patra, S. Nedevschi, S. Surana, A. Sheth, L. Subramanian, and E. Brewer, "Wildnet: Design and Implementation of High Performance WiFi Based Long Distance Networks," in *Proc. Symposium on Networked Systems Design and Implementation*, 2007.

[17] K. Ab-Hamid, C. E. Tan, and S. P. Lau, "Self-Sustainable Energy Efficient Long Range WiFi Network for Rural Communities," in *Proc. IEEE GLOBECOM*, pp. 1050–1055, 2011.

[18] A. Anand, V. Pejovic, E. M. Belding, and D. L. Johnson, "Villagecell: Cost Effective Cellular Connectivity in Rural Areas," in *Proc. 5th International Conference on Information and Communication Technologies and Development*, pp. 180–189, 2012.

[19] A. Dhananjay, M. Tierney, J. Li, and L. Subramanian, "WiRE: a new rural connectivity paradigm," in *Proc. ACM SIGCOMM Computer Communication Review*, vol. 41, pp. 462–463, Aug. 2011.

[20] J. Fitzpatrick, "Voice Call Capacity Analysis of Long Range WiFi as a Femto Backhaul Solution," *Computer Networks*, vol. 56, no. 5, pp. 1538–1553, Mar. 2012.

[21] F. Simba, L. Trojer, B. Mwinyiwiwa, and E. Nerey Mvungi, "Techno-economic Analysis of UMTS900 and UMTS2100 for Rural Connectivity in Tanzania," in *Proc. 14th IEEE International Conference on Communication Technology*, 2012.

[22] I. Siebörger and A. Terzoli, "WiMAX for Rural SA: The Experience of the Siyakhula Living Lab," in *Proc. Southern African Telecommunication Networks & Applications Conference: A Society Enabled by Innovation and Applications*, 2010.

[23] P. Goswami, R. Mahapatra, and Sw. Divyasukananda, "Bridging the Digital Gap in Rural India VIVEKDISHA: A Novel Experience," in *Proc. National Conference on Communications*, 2013.

[24] A. A. Hasson, "The last inch of the last mile challenge," in *Proc. 5th ACM workshop on Challenged networks*, 2010.

[25] S. Isaacman and M. Martonosi, "Low-Infrastructure Methods to Improve Internet Access for Mobile Users in Emerging Regions," in *Proc. 20th International Conference Companion on World Wide Web*, pp. 473–482, 2011.

[26] S. Sarkar, S. Dixit, and B. Mukherjee, "Hybrid Wireless-Optical Broadband-Access Network (WOBAN): A Review of Relevant Challenges," *IEEE/OSA Journal of Lightwave Technology*, vol. 25, no. 11, pp. 3329–3340, Nov. 2007.

[27] A. Achtzehn, M. Petrova, and P. Mähönen, "Deployment of a cellular network in the TVWS: A case study in a challenging environment," in *Proc. 3rd ACM workshop on Cognitive radio networks*, pp. 7–12, 2011.

[28] C. McGuire, M. R. Brew, F. Darbari, S. Weiss, and R. W. Stewart, "Enabling Rural Broadband via TV White Space," in *Proc. 5th International Symposium on Communications Control and Signal Processing*, 2012.

[29] A. M. M. Altrad, W. R. S. Osman, and K. Nisar, "Modelling of Remote Area Broadband Technology Over Low Voltage Power Line Channel," *International Journal of Computer Networks and Communications*, vol. 4, no. 5, Sep. 2012.

[30] D. Fink and R. J. Jeung, "Feasible connectivity solutions of PLC for rural and remote areas," in *Proc. IEEE International Symposium on Power Line Communications and Its Applications*, pp. 158–163, 2008.

[31] A. Sarafi, G. Tsiropoulos, and P. Cottis, "Hybrid Wireless-Broadband over Power Lines: A Promising Broadband Solution in Rural Areas," *IEEE Communications Magazine*, vol. 47, no. 11, pp. 140–147, Nov. 2009.

[32] I. K. Vlachos, "A hybrid W-BPL Smart Grid project in GreeceLessons learnt and next steps," in *Proc. IEEE PES Conference on Innovative Smart Grid Technologies-Middle East*, 2011.

[33] I. Latif, F. Kaltenberger, R. Ghaffar, R. Knopp, D. Nussbaum, H. Callewaert, and G. Scot, "Performance of LTE in Rural Areas-Benefits of Opportunistic Multi-User MIMO," in *Proc. 22nd IEEE International Symposium on Personal Indoor and Mobile Radio Communications*, pp. 2004–2008, 2011.

[34] N. L. Ratnayake, L. N. Atapattu, K. Ziri-Castro, and D. Jayalath, "Efficient Wireless Broadband Communications for Rural Australia," in *Proc. Electromagnetic Compatibility Symposium (EMC Melbourne)*, 2010.

[35] P. Tiwari, "Providing healthcare services in rural India: Innovative application of mobile technology," *Health Care and Informatics Review Online*, vol. 14, no. 2, June 2010.

[36] A. Sharma, E. M. Belding, and C. E. Perkins, "Cell-share: opportunistic use of cellular uplink to augment rural WiFi mesh networks," in *Proc. IEEE 70th Vehicular Technology Conference (Fall)*, 2009.

[37] C. Rey-Moreno, J. Simo-Reigadas, and A. Martinez-Fernandez, "WiMAX-An Uncertain Promise for Bridging the Digital Divide," *IEEE Technology and Society Magazine*, vol. 30, no. 4, pp. 26–33, Dec. 2011.

[38] A. Mary and D. D. Haule, "Modeling of a Broadband Wireless Network for E-health Centers of Rural Coast Region in Tanzania," *Journal of Communication and Computer*, vol. 8, pp. 1057–1063, Sept. 2011.

[39] N. Ndlovu, M. Thinyane, and A. Terzoli, "Deployment and Extension of a Converged WiMAX/WiFi Network for Dwesa Community Area South Africa," in *Proc. Southern African Telecommunication Networks and Applications Conference*, 2009.

[40] F. Simba, L. Trojer, N. H. Mvungi, B. M. Mwinyiwiwa, and E. M. Mjema, "Strategies for Connectivity Configuration to Access e-Learning Resources: Case of Rural Secondary Schools in Tanzania," in *Proc. World Academy of Science and Technology*, 2009.

[41] J. Hartell, "Wireline-based Communication Access Technologies in Rural Kentucky," *http://www.rural.org/publications/reports.html*, accessed Mar. 2013.

[42] Y.-C. Liang, A. T. Hoang, and H.-H. Chen, "Cognitive Radio on TV Bands: A New Approach to provide Wireless Connectivity for Rural Areas," *IEEE Wireless Communications*, vol. 15, no. 3, pp. 16–22, June 2008.

[43] M. H. Omar, S. Hassan, and A. H. M. Shabli, "Feasibility Study of Using IEEE 802.22 Wireless Regional Area Network (WRAN) in Malaysia," in *Proc. 2nd International Conference on Network Applications Protocols and Services*, pp. 198–202, 2010.

[44] H. Suzuki, D. B. Hayman, J. Pathikulangara, I. B. Collings, Z. Chen, and R. Kendall, "Design criteria of uniform circular array for multi-user MIMO in rural areas," in *Proc. IEEE Wireless Communications and Networking Conference*, 2010.

[45] K. A. J. Hay, "Expanding Broadband Access in Rural India: The Role of Alternative Telecommunications Networks," in *Proc. Global Information and Communication Technologies Department Report*, June 2005.

[46] B. Raman and K. Chebrolu, "Lo3: Low-cost, Low-power, Local Voice and Messaging for Developing Regions," in *Proc. Networked Systems for Developing Regions*, 2009.

[47] V. Gabale, R. Mehta, J. Patani, K. Ramakrishnan, and B. Raman, "Deployments made easy: essentials of managing a (rural) wireless mesh network," in *Proc. 3rd ACM Symposium on Computing for Development*, 2013.

[48] P. Mitra and C. Poellabauer, "Emergency Response in Smartphone-Based Mobile Ad-Hoc Networks," in *Proc. IEEE International Conference on Communications*, 2012.

[49] D. Soman, V. Kumar, M. Metcalfe, and J. Wong, "Beyond Great Ideas: A Framework for Scaling Local Innovations," *Rotman Magazine, Rotman School of Management*, pp. 50–55, Sept. 2012.