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Towards a low-cost sustainable broadband solution in rural areas of low and middle-income countries: Tanzania's backhaul perspective

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Abstract

Although broadband internet has proven to accelerate the fulfilment of the information and communication for development (ICT4D) agenda, connectivity issues persist in some regions of the world, particularly in rural areas of Low and Middle-Income Countries (LMICs) which host 93% of the unconnected global population. Due to the lack of economic feasibility in these locations for service providers, International Telecommunication Union (ITU) has been advocating for low-cost sustainable solutions in such areas. Among the challenging broadband infrastructure segment seems to be the backhaul (middle-mile) as rural areas are remotely located from the backbone end-points. With Tanzania exemplifying LMICs, this paper presents a Techno-Economic Analysis (TEA) to compare the widely utilized backhaul (Microwave) and the promising Broadband over Power Line (BPL) towards achieving low-cost broadband solutions. To demonstrate technical viability in terms of capacity, Pathloss and MATLAB were utilized from which both technologies demonstrated the broadband-suitably capacity (161Mbps for Microwave and 168.99Mbs for BPL). From economic perspective, the Total Cost of Ownership (TCOs) for both technologies were determined using a Cost Model; BPL fared better as the cost of establishing one microwave link could have established almost 6 BPL links. Apart from adding to the body of knowledge on TEAs involving backhauls, this paper informs policymakers and other related stakeholders on the potential cost-benefit of BPL towards curbing the existing broadband connectivity gap.

*Keywords:*Backhaul; LMICs; Rural Areas; Broadband; Techno-economic Analysis; Connectivity Gap.

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1. Introduction

Promoting social, economic, and environmental progress as addressed in the 17 United Nations (UN) Sustainable Development Goals (SDGs) can be fast-tracked by the realization of the Information and Communication Technology for Development (ICT4D) agenda, as advocated by several studies (Tjoa & Tjoa, 2016; Wu et al., 2018). Amongst the information and communication technologies (ICT) to expedite the aforementioned task is the high-speed Internet, broadband, which was even agreed to be a basic human right by the UN Key Commission (Melhem, 2016). Broadband can act as a catalyst towards an increased country's Gross Domestic Product (GDP), job creation, broadening of education opportunities, public service delivery, and rural development if the reach, availability, and affordability are guaranteed and the demand-and supply side skills to exploit the economic and innovative potential of broadband are developed (Katz & Callorda, 2018; World Bank Group, 2016).

Not all the global population enjoys the benefits broadband can offer, as some parts of the world are yet to be covered by the technology; the most affected parts are rural areas of developing countries (Broadband Commission, 2022; Lythreatis et al., 2021). With 450 million people yet to be connected, 93% of the global unconnected population is found in Low and Middle-Income Countries (LMICs); hence, this region deserves to be carefully examined if we are to achieve universal connectivity targets by 2030 (GSMA, 2021; ITU, 2022). The reasons for such a huge connectivity lag in LMICs have been found to be a lack of access to broadband services due to the absence of infrastructure (Connected Society, 2016; Kalula et al., 2022; Marcus & Wong, 2016). Mobile Network Operators (MNOs), being the major broadband service providers, do not have the potential to invest in rural areas, as their business model serves better in urban areas (Cruz et al., 2018). As rural areas are characterized by low-income and sparsely inhabited populations, infrastructural investment is not attractive to MNOs because the return on their investment is not guaranteed (Prieto-Egido et al., 2020; Saeed & Masakure, 2016).

The International Telecommunication Union (ITU) has been advocating low-cost and sustainable solutions to address rural connectivity challenges, thereby lowering Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) for service providers (ITU, 2021). Low-cost and sustainable broadband solutions would not be complete without encompassing cost-effective backhaul, a means of delivering the signal from backbone endpoints to the access part in rural areas (Anusha et al., 2017; Kumar et al., 2022). Henceforth, The future of broadband services is heavily reliant on a range of high-performance and cost-effective backhaul solutions, and this network component must be examined to achieve low-cost broadband solutions (Saunders & Marshall, 2018).

As the backhaul's capacity requirements have been tremendously increasing with the birth of broadband, a careful analysis looking at both technical and economic aspects is if utter importance. Technical-wise, the performances of broadband networks have always been measured in both capacity and long-distance reach perspectives (Ahamed & Faruque, 2018). Traditional copper backhauls are being phased out because of capacity issues over long distances; a newly discovered bonding technique to increase capacity has been devised, but it has cost implications (Farias et al., 2016; Mahloo et al., 2014; Saunders & Marshall, 2018). In cases where service providers face inhospitable terrain and line-of-sight restrictions, satellites offer the quickest means of service deployment (del Portillo et al., 2021). However, satellite latency and prohibitive data costs render them unsuitable for addressing the coverage of rural areas (Araújo et al., 2019). Fiber backhauls remain a good option for bandwidth-hungry applications and cover long distance with minimum attenuation (Zeydan et al., 2021). However, the cost of laying down fiber (trenching, right of way, etc.) limits its use as a backhaul to extend services to rural areas (Araújo et al., 2019). Microwave technology offer an alternative to hard-to-reach areas where fibers and other wired backhauls are of no use (Sharma et al., 2021). Its capacity can always be increased to multiple gigabits per second (Gbps) using aggregation techniques (Kouchaki & Dabibi, 2020). Nevertheless, microwave covers only a maximum of 30 miles requiring relay stations for longer reach and may suffer disruption on bad weather (Thakur, 2018). Deviating from the traditional backhauls, Broadband over Powerline (BPL) has also been used for broadband backhaul as it has been proven to offer capacity of up to 500Mbps physical (PHY) layer operating at a frequency below 100 MHz (Slacik et al., 2021). However, this technology works well with Medium Voltage; MV (1,000-35,000 Volts) and Low Voltage; LV (120/240 Volts) as High Voltages; HV (155,000 – 765,000 Volts) are prone to interference that may occur due to spiking frequencies, resulting in damage to the RF signal being carried along (Hossain et al., 2014).

On deciding which backhaul technology to adopt for rural connectivity, Techno-economic analysis (TEA) offers the best way to assess the viability of technologies by integrating both technological and economic feasibility (Chai et al., 2022). Several TEAs have been done across several existing backhaul technologies to address the rural connectivity gap, to mention but a few; Araújo et al (2019), del Portillo et al (2021), Kolydakis and Tomkos (2014) and Prieto-Egido et al (2020). However, to the best of the authors' knowledge, none of the TEAs have involved the broadband over power line (BPL). Considering the potential BPL offers when it comes to broadband backhauling as reported by Slacik (2021), this paper aims to present TEA involving it and the mostly used backhaul technology in the LMICs; Tanzania considered as a case study. Looking from a theoretical perspective, this paper contributes TEA involving microwave and BPL technologies in the backhaul link toward achieving a low-cost broadband solution suitable for rural areas in the LMICs. The study lays out insightful implications for stakeholders (policymakers, MNOs, etc.) on the way the suggested backhaul can best be put into use.

The remainder of this paper is organized as follows. Section 2 presents the rural connectivity initiatives in Tanzania. Section 3 briefly describe the study motivation while section 4 presents the TEA's related studies. Section 5 offers the methodological part. TEAs for the chosen technologies are presented in section 6 while section 7 presents the results. The section concludes the study.

2. Rural Broadband Connectivity Initiatives in Tanzania

Tanzania, with a population of around 61 million people, with 66% found in rural areas, has been implementing several initiatives to address connectivity in rural areas (NBS, 2022; World Bank, 2018). Among these initiatives is the National ICT Broadband Backbone (NICTBB) project, which has so far delivered over 8,319 km of fiber backbone, reaching almost all the districts in the country (NICTBB, 2022), as depicted in Figure 1. However, it is understandable that rural areas extend beyond districts and major towns; hence, the backbone's end-point extension to rural areas is essential. Meanwhile, the government established a Universal Communication Service Access Fund (UCSAF) to fuel rural connectivity by funding service providers to establish communication services in unserved rural areas. Nevertheless, service providers involved in UCSAF projects have pointed out that extending services from NICTBB's Points of Presence (PoPs) to rural areas has been very challenging both economically and technically (Kalula et al., 2022).

3. Study Motivation

The analysis involving BPL in this study is motivated by the remarkable job that has been done by the Rural Electrification Agency in Tanzania (REA). Currently, 8547 of 12345 villages in Tanzania are beneficiaries of the electrification project. Phase III of the REA project is underway to complete electrification for the remaining 3978 villages; hence, all villages in Tanzania will soon have electric energy (Makamba, 2022). REA extends medium-voltage lines from substations at the district level to rural areas over wooden/concrete poles. Notably, the fiber backbone network in Tanzania has its PoPs in almost every district in the country (Figure 1), locations with power substations where REA picks energy for transmission. The fact that broadband can be transmitted over power lines brought about the idea of conducting a techno-economic study to compare it with existing backhaul solutions and to see if it can offer a cost-effective solution for broadband access in those areas that benefit from REA projects but have no coverage.

Figure 1: Tanzania fiber Optic backbone network by NICTBB (NICTBB, 2022)

4. Related TEA Works

To bridge the digital divide in rural parts of the world, hence pushing the ICT4D agenda towards achieving the UN's SDGs, researchers should not only concentrate on technical aspects as economic parameters but also need to be looked at (Krizanovic Cik et al., 2018). There is a relationship between the infrastructure cost (both CAPEX and OPEX) and service affordability; hence, cost-effective infrastructural solutions are necessary to push the affordable broadband adoption agenda in rural areas, thus realizing

ICT's contributions to personal and countries-level economies (Chiha et al., 2020; Webb, 2015). Backhaul was presented as a stumbling infrastructural block by Kalula et al. (2022), Mahloo et al. (2014) suggested a detailed TEA for several existing backhauls to achieve a cost-effective backhaul.

With the recent decrease in Average Revenue Per User (ARPU), TEA is becoming essential in investment decisions for MNOs/service providers when it comes to delivering broadband services, especially in rural areas (Mahmood et al., 2019; E. J. Oughton et al., 2022). Several backhaul TEAs were conducted as described herein. Kolydakis and Tomkos (2014) conducted a TEA from the Total Cost of Ownership (TCO) perspective between fiber and point-to-point microwaves in delivering services to access part of the hypothetical deployed mobile network; the latter became favourable for longer distances. However, fiber technology works well for very dense LTE network provision in city centers for distances of Ds< 1 km. The fact that fiber technology is expensive when run over a long distance makes it unsuitable for delivering access to rural areas, as the return on investment is not guaranteed (Sharma et al., 2021).

Moreover, Prieto-Egido et al. (2020) conducted a techno-economic analysis comparing satellite and terrestrial microwaves to bring broadband to rural Peru. Using appropriate low-cost technologies and an inventive business model supported by regulations, this study evaluated a viable and long-term plan to introduce mobile communication services (voice and data) in remote settlements in developing nations with less than 1000 residents. A very small-aperture terminal (VSAT) was initially deployed and yielded data for satellites but was only replaced by terrestrial microwaves because the cost for satellites proved to be unaffordable. In conclusion, for this particular study, terrestrial microwaves performed better cost-wise, but still MNOs/service result to it as being expensive for service provision in most of the rural settings where their business model could have failed, hence the still existing connectivity gap.

Del Portillo (2021) created a techno-economic technique to evaluate the potential influence of space and aerial concepts in extending connectivity to untapped and underserved places. In particular, massive constellations of medium-earth orbit (MEO) and low-earth orbit (LEO) satellites, constellations of Geostationary Orbit (GEO) satellites, and high- and low-altitude airborne platforms have been investigated. The findings demonstrated that, in the current scenario, the impact of space and aerial systems on enhancing connectivity would be relatively modest; the current cost of satellite technology (roughly \$200 per Mbps/month) is affordable for less than 1% of the unconnected and underserved population in the countries of interest. Looking at the income of the majority of rural dwellers, the proposed solution still looks expensive, and hence, a still persisting connectivity gap.

Araújo et al. (2019) did a techno-economic analysis of optical fiber with satellite for the middle mile from an economic and financial standpoint while presenting a simulation model for the backhaul infrastructure expenses for very fast networks in rural areas of Europe to cover the last and more expensive 5% of the population. The study evaluated both possibilities of using optical fiber against satellites for broadband backhaul and showed that, for very low household densities, the satellite is substantially more cost-effective. However, looking at the demographic features (e.g., income) of the population in rural Europe compared to most of the LMICs gives an insight into the persisting connectivity gap, since not necessarily what works in rural Europe will work in rural areas of LMICs.

To the best of our knowledge, none of the techno-economic analyses performed on the backhaul (middle-mile) part has included BPL as a potential backhaul technology comparing it with others. The fact that BPL has been proven to offer a speed beyond the defined broadband speed made it suitable for the group of potential backhaul technologies; hence, a techno-economic study involving it is essential (ITU, 2017; Slacik et al., 2021). Henceforth this study conducts the TEA between BPL and the global mostly used broadband technology (microwave) (Bovberg, 2016; Saunders & Marshall, 2018).

5. Method

In a reported study, TEA was used, as this technique suitably helps to quantitatively evaluate the cost performance of different engineered systems (Kobos et al., 2020). Since the study seeks to inform stakeholders (service providers, policymakers, etc.) how backhaul engineering can aid in achieving a low-cost broadband solution, TEA offers opportunities when it comes to assessing the commercial viability of the investments and hence inputs to strategic plans and investment decisions (E. Oughton & Lehr, 2021). To carry out TEA, engineering specifications for backhauls suiting broadband were revisited for the chosen technologies with respect to their performance. Pathloss and MATLAB were used to simulate the two technologies being compared, showing the capacity that each technology can achieve in the chosen environment. With capacity already determined, link dimensioning was then performed by identifying assets and all affiliated components, sometimes referred to as a bill of material. Data used for the link dimensioning process were sourced from renowned vendors in the telecommunications field, particularly those working in the backhaul segment. Based on the bill of materials developed, the Cost Model was employed to establish the TCO capturing both CAPEX and OPEX. The TCO offers a great way to provide only a side-by-side cost comparison to the two different solutions at hand. Figure 2 summarizes the Cost Model framework.

5.1 Cost Model Formulation

Arriving at the TCO requires mathematical calculation from each of the individual cost models (as shown in Figure 2) considering their CAPEX and OPEX. CAPEX refers to all backhaul deployment costs, divided into two parts: equipment and infrastructural costs. In addition, the OPEX refers to expenses incurred in running the network over a predefined time interval (five years in this study); these include maintenance cost, fault management cost, training costs, land rent, etc. Moreover, engineering work involves unforeseen circumstances; hence, overhead costs must be considered during planning. The mathematical formula for obtaining the TCO for each of the compared technologies is presented in Eqn (1).

$$TCO = CAPEX + \sum_{i=1}^{5} OPEX + Overhead \tag{1}$$

5.2 Study Area

The study area for the reported research was chosen to be the path between Chemba Town and Donsee Village, both found in Dodoma, the central part of Tanzania. Tanzania, among LMICs, has featured well, exemplifying other countries when it comes to the connectivity gap; it has been reported that 86% of rural dwellers are yet to be connected to the Internet (RIA, 2017). Moreover, the telecommunication regulatory body's latest reports show that Tanzania's Internet penetration continues to slow as most of the profit potential areas are already connected; growth has been only by 6% between the years 2016-2020 compared to 15% between the years 2011-2015 (TCRA, 2021). The areas to conduct TEA within Tanzania were chosen, as they fit the criteria listed herein.

1. One side should have a fiber broadband PoP service provider, as well as a power transmission substation, Chemba.
2. The other side should have electric power with the MV running from the other side of the power substation, Donsee.
3. Researcher's convenience in obtaining data from the site and relevant authorities.

The aim is to deliver broadband service at Donsee with a population of approximately 1000 people (NBS, 2022), which will be sourced from Chemba, where NICTBB's PoP is located. The distance between Chemba and Donsee is approximately 40 km. Donsee is among the beneficiaries of the rural electrification project for the 33 KV MV lines built from Chemba Town along a 40 km road connecting the two places. The area between the two locations is a semi-flat mountainous terrain with trees not beyond 12m. An aerial photograph of the study area is shown in Figure 3.

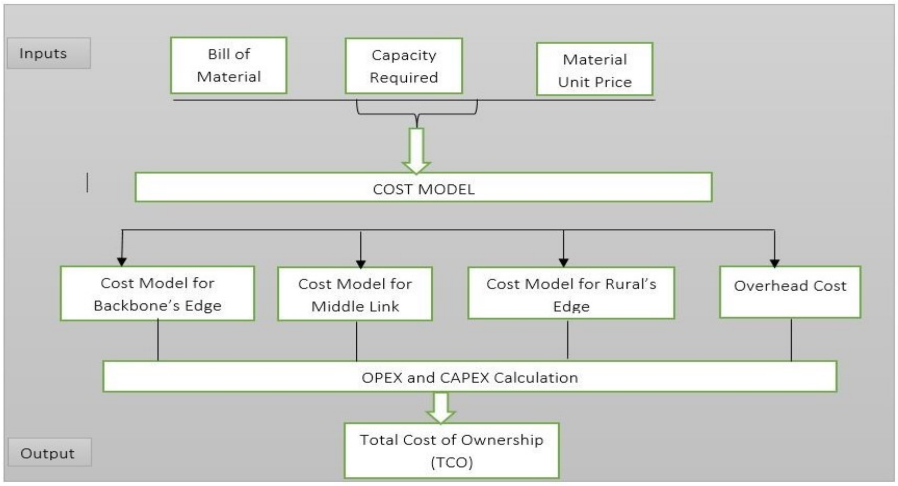


Figure 2: Cost Model framework

5.3 Data Sources to Conduct TEA

As far as the technical part was concerned, the data to conduct path analysis for microwave links were sourced from the site chosen for the study, the country's regulatory authority, the country's agency responsible for fiber optic backbone network, and prediction data based on ITU recommendations (ITU-R P.530-16). For the BPL's technical analysis, the data were sourced from the site chosen for the study, while information and data for power line infrastructure were obtained from the country's rural electrification agency (REA) and the past literature on BPL.

Figure 3: Chemba-Donsee aerial photo (courtesy of Google Earth)

6. Techno-economic Analysis

6.1 Overview of Backhaul Technologies for Rural Coverage

A broadband network typically consists of two primary parts: the access network (last mile) and the backhaul (middle mile) network. While the backhaul network links all of the service provider's POPs to carry aggregated subscriber traffic, the access network provides last-mile connectivity between subscriber/premises and the nearest node or POP. The primary necessity of broadband services in rural areas is how to transport data capacity to and from the Access node and centralized node of core network, regardless of the technology chosen for the Access. The speed of the backhaul connection to the access node should be at least 100 Mbps and occasionally even more to the neighbouring point of presence (PoP). Various wireline and wireless-based technologies are available for access and backhaul networks to deliver end-to-end broadband services; the backhaul technologies are expounded herein.

With regard to future-oriented high-speed broadband applications, optical fiber-based transmission systems have large capacity and are appropriate for the backhaul portion of broadband. Modern fibers can multiplex up to 160 signals each with 1.6 Gbps amounting to a total of 1.6 Tbps for one link (Saunders & Marshall, 2018). Costly fiber deployments don't make a lot of financial sense in rural locations because to the low population density and thus low Average Revenue per User (ARPU). For MNOs, the return on investment (ROI) of fixed telecom solutions will fall short of expectations.

Microwave technology uses both the licensed spectrum (2-40GHz) and unlicensed one (2.4GHz & 5GHz). Microwave solutions seem to fit in rural settings, as establishing the Line of Sight (LOS) requirement for such areas is not a problem as it is for metropolitan areas (Hansryd et al., 2014). It has two architectures, point-to-point (PTP) and point-to-multipoint (PMP), both of which have a capacity of several hundred megabits per second (Mbps). Utilizing low frequency group radios, operators can easily construct long-distance networks with a hop distance of over 30 km, and with advance planning, linkages up to 130 km. With the invention of new high-capacity techniques, microwave radios now have the ability as alternatives to fiber at a lower cost and meet the expanding demand for broadband services in rural areas.

For remote and difficult-to-access areas, satellite backhaul services have advantages over traditional backhaul choices that are unmatched. Satellites have been successfully serving the traditional markets, such as telecommunications and TV, by using a single beam or transmission to reach vast geographic areas. The footprint of satellite operators is almost limitless. Rain attenuation has a substantial impact on satellite high frequencies, especially in tropical areas where the impacts might be as low as 7 GHz. Moreover, the technology is unsuitable for rural economic situations due to its high costs and latencies brought on by the signal's distance travelled.

Microwave technology is the lead backhaul technologies being employed globally by service providers, making up more than half of the global backhauls (Bovberg, 2016; Saunders & Marshall, 2018). Narrowing down to Sub-Saharan Africa (SSA), the most commonly used backhaul technology is terrestrial microwave (85.3%), followed by fiber-optic (4.3%) (GSMA, 2018). Moreover, while there isn't a TEA that combines microwave and BPL, the potential that BPL has demonstrated for delivering broadband signals supports the case for doing so.

6.2 TEA for Microwave Technology

This technology is deployed at a bandwidth of 28 MHz, which is normally assigned by the country's regulatory authority for microwave installations. To deliver broadband service 40 km away from the backbone PoP, a point-to-point microwave was employed; 1.8m antennas using 7 GHz transmission frequency while exploiting 128QAM purposely to achieve 99.999% link availability; the major concern at hand was getting the data rate fitting in the broadband definition as per ITU (2003). Parameters for propagation data and prediction methods required for the design of terrestrial line-of-sight systems were used as stipulated in the recommendation ITU-R P.530-16, in which the area where the design was carried out belonged. To overcome the effects of the earth bulge resulting from the physical earth curvature along the direct path between Chemba and Donsee, 40m towers were deployed at both ends with the antenna placed 36m above the ground, as shown in Figure 4. The link summary after the configuration is provided in Figure 5. Huawei Radios were selected at both ends with a transmission power of 26dBm configured with a threshold received signal level of -72.5 dBm (minimum BER 10-6). With 128QAM vertical polarization, 161 Mbps was achieved, which can serve the purpose as far as broadband is concerned.

Table 1 shows the list of equipment needed at both ends of the link alongside their costs, which were derived by conducting market research for the year 2022 from different renowned vendors, such as Aviat, Ceragon, Huawei, and Ericsson. The price for equipment was put in United States dollar USD, as it is the most stable currency and hence less volatile (Eichengreen et al., 2022).

The total equipment cost together with the installation cost constitutes the CAPEX using Eqn (2), where CostEq and CostInst represent equipment and installation costs, respectively. CostInst is calculated to be 15% of the total equipment's cost as per Casier (2010)

$$CAPEX_{MW} = Cost_{Eq} + Cost_{Inst} \tag{2}$$

When it comes to OPEX, it is calculated as 10% of the CAPEX (Casier, 2010), as seen in Eqn (3). The OPEX will be estimated for a period of 5 years as stipulated in the methodology part, it is assumed to be constant for the whole duration.

$$OPEX_{MW} = 10\% \times CAPEX_{Eq} \times 5\,years \tag{3}$$

With both CAPEX and OPEX for microwave technology to cover the aforementioned link, the overhead cost was calculated as 22% of the total cost (Casier, 2010). Using Eqn (1), the TCO is calculated to reflect the deployment.

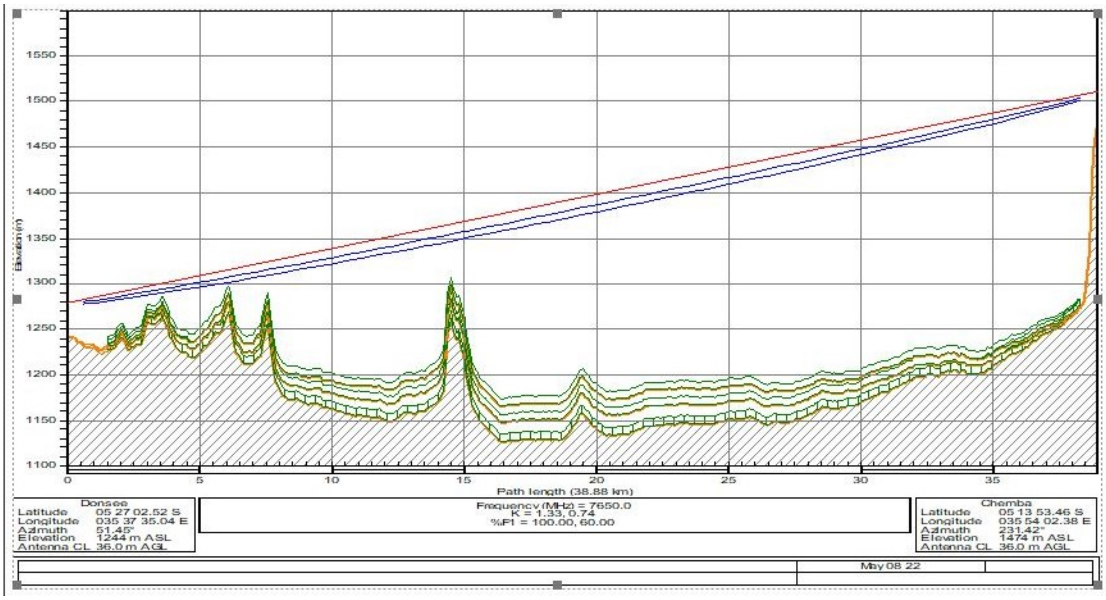
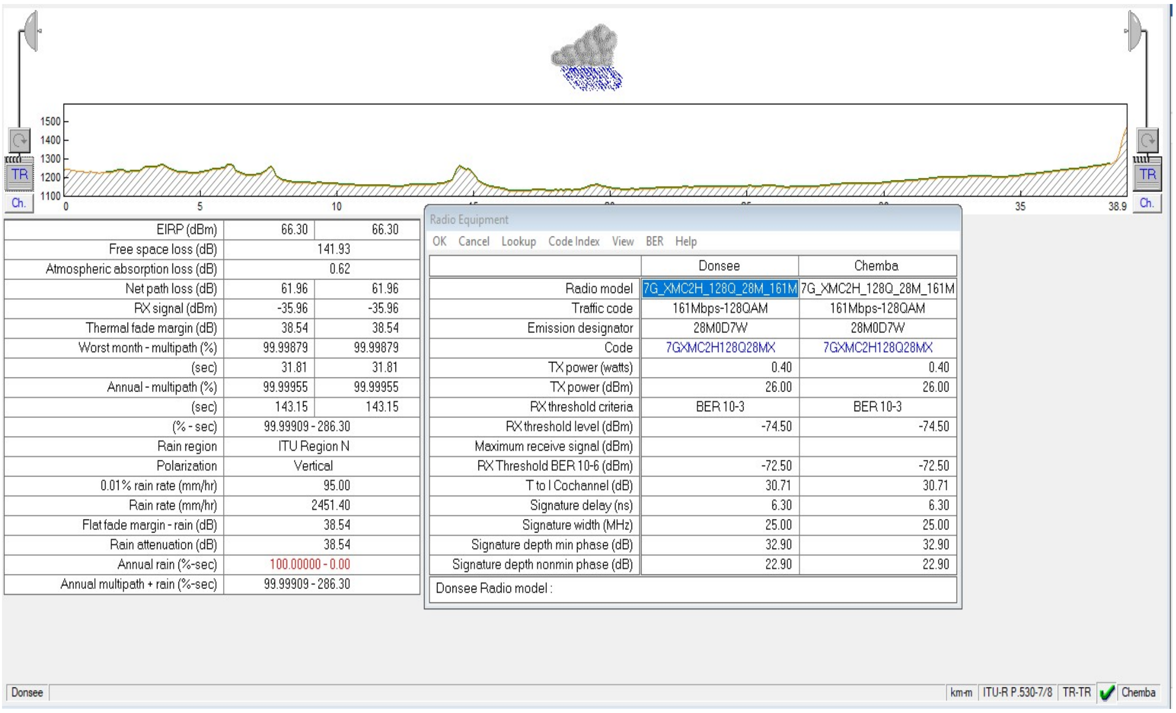


Figure 4: Chemba-Donsee link profile



EIRP (dBm)	66.30	66.30
Free space loss (dB)	141.93	
Atmospheric absorption loss (dB)	0.62	
Net path loss (dB)	61.96	61.96
RX signal (dBm)	-35.96	-35.96
Thermal fade margin (dB)	38.54	38.54
Worst month - multipath (%)	99.99879	99.99879
(sec)	31.81	31.81
Annual - multipath (%)	99.99955	99.99955
(sec)	143.15	143.15
(% - sec)	99.99909 - 286.30	
Rain region	ITU Region N	
Polarization	Vertical	
0.01% rain rate (mm/hr)	95.00	
Rain rate (mm/hr)	2451.40	
Flat fade margin - rain (dB)	38.54	
Rain attenuation (dB)	38.54	
Annual rain (%-sec)	100.00000 - 0.00	
Annual multipath + rain (%-sec)	99.99909 - 286.30	

	Donsee	Chemba
Radio model	7G_XMC2H_128Q_28M_161M	7G_XMC2H_128Q_28M_161M
Traffic code	161Mbps-128QAM	161Mbps-128QAM
Emission designator	28M0D7W	28M0D7W
Code	7GXMC2H128Q28MX	7GXMC2H128Q28MX
TX power (watts)	0.40	0.40
TX power (dBm)	26.00	26.00
RX threshold criteria	BER 10-3	BER 10-3
RX threshold level (dBm)	-74.50	-74.50
Maximum receive signal (dBm)		
RX Threshold BER 10-6 (dBm)	-72.50	-72.50
T to I Cochannel (dB)	30.71	30.71
Signature delay (ns)	6.30	6.30
Signature width (MHz)	25.00	25.00
Signature depth min phase (dB)	32.90	32.90
Signature depth nonmin phase (dB)	22.90	22.90

Donsee Radio model :

Figure 5: Configured link with parameters

6.3 TEA for BPL Technology

In deploying BPL, the existing power line utilities are used; hence, there is no need to erect fresh infrastructure, and the only investments in this technology will be for purchasing broadband equipment. Because Tanzania is considered a case study, electric power lines installed by the country's rural electrification agency, REA, were exploited. The parameters to be used in the BPL's TEA were adopted from the existing REA infrastructure, and similar studies were conducted within the same area. Figure 6 shows the BPL infrastructure as per the defined study area, and the link properties are adopted from REA's existing power network. The 33 MV line was installed along a 40 km road connecting Chemba and Donsee, and wooden utility poles of 10m height were placed after each 100m.

Table 1. Bill of material for microwave link

Bill of Material for Microwave link (IP); 40 Km HOP, 1+0 Conf (full outdoor)				
S/N	Item	QTY	Unit Price (USD)	Total (USD)
1	Tower Installation 40m	2	17200.00	34400.00
2	Backup Battery	8	650.00	5200.00
3	Rectifier	2	4290.00	8580.00
4	Microwave Antenna, 1.8m (Both Ends)	2	3635.00	7270.00
5	Radio 7GHz Outdoor Unit (Both Ends)	2	650.00	1300.00
6	50m Outdoor LC-LC Fiber Cable (Both Ends)	2	12.00	24.00
7	Baseband Outdoor Unit 1xIF port(Both Ends)	2	490.32	980.64
8	Small Form-factor Pluggable, SFP (Both Ends)	2	108.00	216.00
9	Installation Accessories (IF Connectors, Installation tap, cable ties, IF cable, Power cable, Cable clamps etc.)	N/A	329.00	329.00
	Total Costs (CostEq)			58299.64
	Installation Cost (CostIns); 15% of Cost Eq			8744.95
	CAPEX			67044.59

The signal from the NICTBB's PoP is passed through an MV Concentration Unit (MVCU)/injector, which changes it to a form suitable for transmission over the power line. The signal is fed into the power line using an injector. An inductive signal is preferable because it avoids physical connectivity with a live line (Anushree et al., 2014) (see Figure 6). Orthogonal Frequency-Division Multiplexing (OFDM) is exploited as a modulation technique owing to its better spectral efficiency and robustness in channel distortion, as electrical lines tend to be noisy (Mahmood & Salih, 2019). Because there is a limited distance for the signal to travel over power lines before decaying, a repeater was deployed to re-amplify the signal. The distance depends on many parameters, including the type of cable/line, presence of cable box, bus bar placement, and type of couplings (Debita et al., 2019). The repeater type used in this TEA is no more than 5 km. Since this study intended to cover 40 km, repeaters were deployed approximately every 5 km. At the end of the link, an extractor/MVCU is installed to extract the broadband signal.

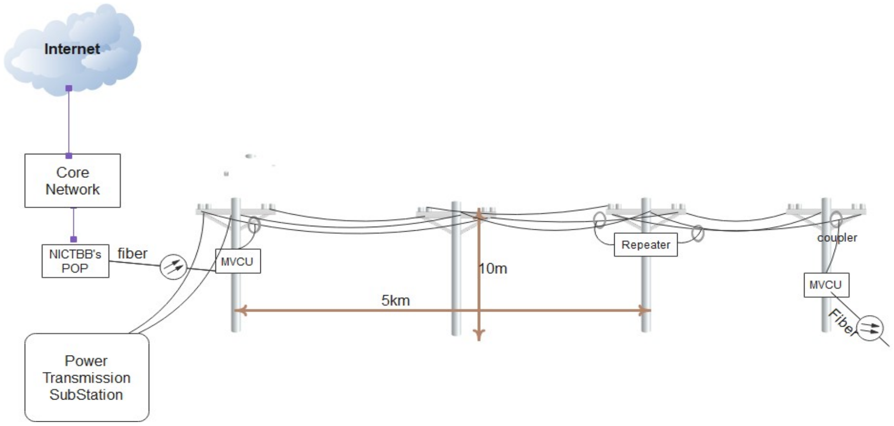


Figure 6:MV BPL infrastructure

To show how much capacity can be achieved with BPL, a 3-phase REA's MV topology of the REA utility project is assumed; phases are separated by 0.3m apart. A 1000m hop was considered with poles placed every 100m; Aluminium conductor steel-reinforced, ACSR 100 mm^2 cable used with Wire to Ground, WTG opted for signal injection with Differential Mode coupling. To fit the real deployment scenario, the hop is assumed to have three branches located at distances *D1= 500m, D2= 200m, D3=100m,* and *D4= 200m* (topology is shown in Figure 7). The conductivity of the ground is assumed to be $\sigma_g = 1\text{mS/m}$ while its relative permeability is taken to be $\varepsilon_g = 10$ being a typical value for most ground conditions. The unit length parameters for the REA lines were adopted from Anatory et al. (2007) on a typical MV line of the Tanzania's MV power network.

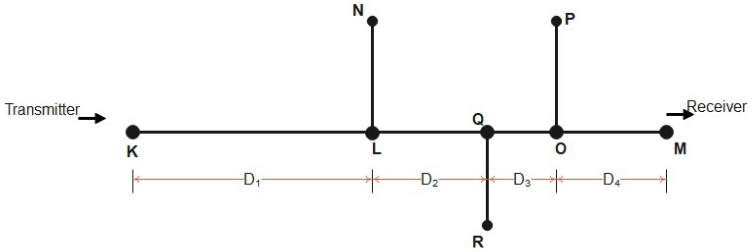


Figure 7:MV topology with three branches

The Multipath Echo-Based (MEB) model is used because it was developed to describe transmission along the power grid based on multipath consideration of the MV BPL. Signal transmission occurs not only from the transmitter to the receiver; signal echoes from points of impedance discontinuities must also be considered (Chelangat, 2018). Moreover, Shrestha (2019) highlighted the importance of concentrating on the propagation phenomena of a communication signal in an active electrical network, rather than on the physical properties and parameters of the network, to facilitate the creation of resilient and reliable signal-processing algorithms. Therefore, the multipath channel model proposed by Zimmermann and Dostert (2002) was employed in this study to express the channel transfer function of a power line using a closed form equation. Thus, the transfer function is described by

$$H(f) = \frac{z_{in}(f)}{z_{in}(f) + z_g} \sum_{i=1}^{N} | g_i | e^{j\varphi_i} e^{-a(\omega)L_i} e^{-j\beta(\omega)L_i} \tag{4}$$

Where $g_i = | g_i | e^{j\varphi_i}$ is a weighting factor being the product of reflection and transmission coefficients along the path i, L_i being the path length, $e^{-a(\omega)L_i}$ being corresponding attenuation factor, $e^{-j\beta(\omega)L_i}$ being the corresponding delay factor, and N is the number of dominant paths (*N*= *1* in this study). Using Eqn (4), the plot for attenuation vs frequency is produced as shown in Figure 8. The spectral notches observed in Figure 8 are caused by reflections at different frequencies due to impedance mismatches and multipath propagation caused by junctions and branches on the defined MV hop.

The channel capacity is calculated from Eqn (5), inherited from Anatory et al. (2007), where the frequency variation is between 0.3–30MHz.*S(f)* denotes the received signal power, which is determined by the transmitted signal power and channel transfer function H(f), as shown in (6); PSD stands for power spectral density. The noise power levels, *N(f)*, for different frequencies were adopted from Bai et al. (2020). The field strength is limited to 30μV/m considering the limitation of the transmit power (10 dBm). For this study, the chosen PSD was in the range of -60 dBm/Hz to -30 dBm/Hz. The channel capacity over the MV BPL was calculated as 168.99 Mbps.

$$C = \int_{r_1}^{r_2} \log_2\left[1 + \frac{S(f)}{N(f)}\right] df \tag{5}$$

$$S(f) = PSD.\left|H(f)\right|^2 \tag{6}$$

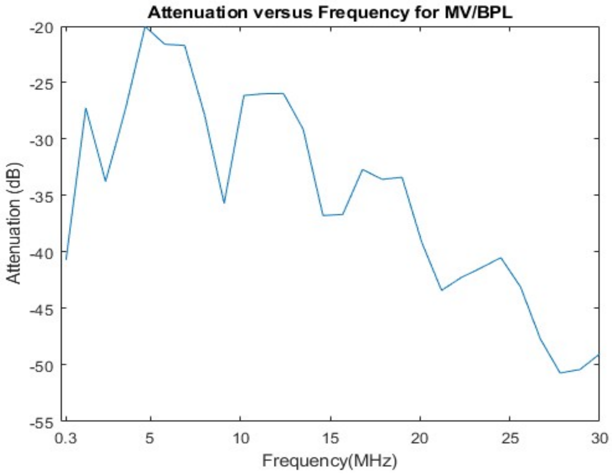


Figure 8: Spectral behavior for signal propagation over MV

Moving ahead to the economic analysis, the bill of material for the aforementioned BPL link was established, as shown in Table 2. The indicative unit prices for the equipment/materials are gathered by conducting market research for the year 2022 from renowned BPL vendors, such as Corinex, Wondershek Kushan Technology, and Premo. The price for equipment were put in USD as it is the most stable currency hence less volatility (Eichengreen et al., 2022).

The OPEX for BPL was calculated as it was for microwave; 10% of the capex using Eqn (7). The Opex is estimated for a period of five years, as stipulated in the methodology section.

$$OPEX_{BPL} = 10\% \times CAPEX_{BPL} \times 5\,years \tag{7}$$

Having calculated both CAPEX and OPEX, the TCO for BPL can now be estimated by using Eqn (1). Overhead cost is calculated as 22% of the total of Opex and Capex (Casier, 2010).

Table 2. Bill of material for BPL link

LIST OF MATERIAL FOR BPL 40KM LINK OVER 33KV EXISTING PUBLIC UTILITY INSTRASTRUCTURE				
S/N	ITEM	QTY	UNIT PRICE (USD)	TOTAL (USD)
1	50m LC-LC outdoor Fiber cable	2	12.00	24..00
2	Repeater Unit (Injection &Extraction embedded)	10	310.00	3100.00
3	Coupler	18	375.00	6750.00
	Total Cost; CostEq			9874.00
	Installation Cost (CostIns); 15% of CostEq			1481.10
	CAPEX			11355.10

7. TEA Evaluation Results

7.1 Technical Perspective

From a technical perspective, both microwave and BPL have proven to offer an acceptable capacity as per the broadband standards defined by the ITU. BPL gave a channel capacity of 168.99Mbs while the microwave gave a 161Mbps channel capacity (Figure 9). Both capacities can be improved by further reengineering procedures. For BPL, only one phase was used for the aforementioned capacity, which could have doubled or tripled with the use of two or three phases, respectively. However, this also has cost implications. The same applies to microwaves; aggregation techniques could have increased the capacity but also had cost implications. Henceforth, both technologies offer technically viable solutions capacity-wise to cater to the rural digital divide in Tanzania and other LMICs with similar settings.

Despite both technologies conforming to the broadband definition as far as channel capacity is concerned, BPL has been faced with implementation obstacles. Among these obstacles is the significant potential interference with services operating at the same frequency level as the BPL, amateur radios, shortwave broadcasts, emergency radio services, citizen band radios, and aeronautical ground station professionals. However, equipment designed to use frequency notching and power control techniques can address the potential interference issues. It is important to note that most of the LMICs' spectrum range potential for BPL is yet to be occupied by the aforementioned services, hence providing good prospects for BPL deployment. It is understandable that BPL has not gained traction in many LMICs, probably because of its discontinuance history in some developed countries due to limited reach and low bandwidth (introduction of 3G, 4G, and 5G), but this cannot stop using it to address rural broadband coverage in a cost-effective manner, as long as there exists an MV network. The issue of network reach is addressed by the use of repeaters, for which there are still vendors dealing with BPL equipment conforming to the established IEEE standard for BPL; IEEE 1901-2020.

7.2 Economic Perspective

As mentioned earlier, the challenge that many service providers face with backhaul is the cost involved; thus, the focus should be turned to cost assessment to achieve a cost-effective solution. Figure 10 shows the TCO results for both the microwave and BPL; the BPL appears to have a low TCO. The figure expounds on the cost analysis part by showing the cost composition for each technology in terms of CAPEX and OPEX.

BPL's cost-effectiveness of the BPL is due to the fact that the existing electric utilities (poles and wires) were utilized, adding only a few pieces of equipment for broadband signal transmission. A higher percentage contribution to the BPL's CAPEX is on the middle link of the backhaul, which involves the purchase of couplers and repeaters to maintain the signal strength in the course of transmission. The considerable increase in the microwave TCO was mainly due to the installation of infrastructure at both ends of the assumed study area. From the TCO point of view and the fact that rural electrification plans are underway in many parts of LMICs, BPL can be opted for as a cheaper backhauling method than microwave. Low-cost backhaul twinned with a low-cost last-mile solution will eventually result in affordable broadband solutions in rural areas, thus pushing the broadband adoption agenda toward realizing ICT4D.

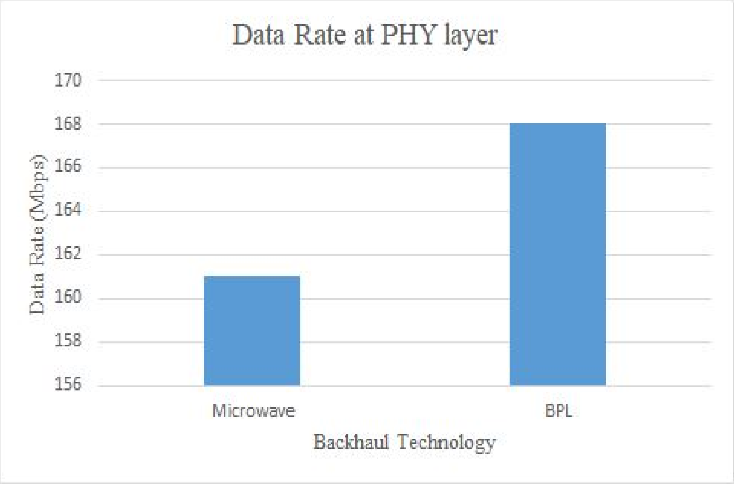


Figure 9: Data rate at PHY layer

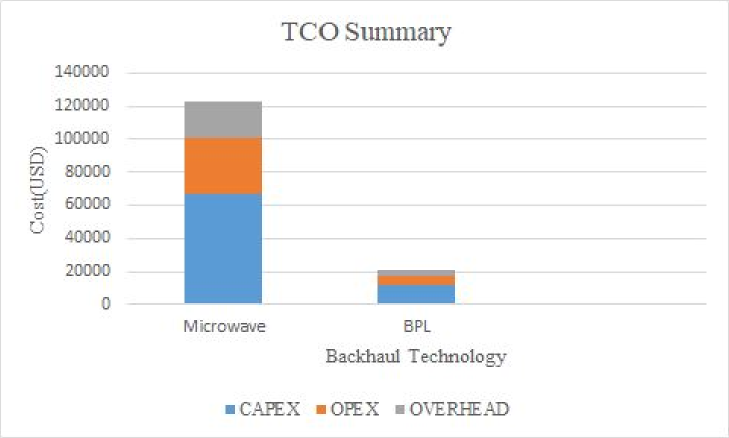


Figure 10:TCO summary

8. Conclusion

This paper presented the TEA from the TCO perspective, considering backhaul links for bringing broadband service to rural areas of LMICs; Tanzania was chosen as a case study. Microwave and BPL technologies were analysed technically for the chosen area based on the channel capacity that can be produced at the physical layer. BPL slightly outweighed the microwave technology. Nevertheless, all technologies provided capacity suitable for broadband, referring to ITU's broadband definition. In Tanzania's case, where NICTBB has PoPs in almost every major town in the country, the extension of PoPs to rural areas for broadband provision is technically feasible for both technologies.

This study has implications for policymakers, as it provides insights into how broadband signals can be delivered in rural areas in a cost-effective manner. At a high time, policies have been revisited to enable power utility companies to work with universal access funds to exploit power lines for broadband transmission. For example, Tanzania Electric Supply Company (TANESCO) and the UCSAF can work together to deliver broadband services to unserved areas. Moreover, regulatory bodies must lay out plans in their spectrum assignment on how interference issues for BPL with other applications (happening to use the same frequency bands) are addressed as BPL implementations were faced with obstacles in other countries.

Several backhaul TEAs were performed using several technologies (fiber, copper, satellite, and copper), and each delivered comparison results to achieve a low-cost rural broadband solution. However, none of the TEA has ever involved BPL (considering its potential) and renowned backhaul technologies. This study hence did the same comparing BPL and Microwave. It adds to the literature on TEAs involving BPL to curb the existing digital divide in a cost-effective manner without compromising service quality as far as broadband is concerned. Cost-effective backhauls imply low-cost broadband solutions and access to broadband services to rural dwellers, pushing the realization of the ICT4D agenda and alleviating the disadvantages of remoteness. As a future research, a simulation of scenarios to demonstrate the techno-economic capabilities of the two technologies should be considered.

References

Ahamed, M. M., & Faruque, S. 2018. 5G backhaul: Requirements, challenges, and emerging technologies. *Broadband Communications Networks: Recent Advances and Lessons from Practice*, Vol. 43, 2018. http://dx.doi.org/10.5772/intechopen.78615

Anatory, J., Theethayi, N., Thottappillil, R., Kissaka, M. M., & Mvungi, N. H. 2007. Broadband power-line communications: The channel capacity analysis. *IEEE Transactions on Power Delivery*, Vol. 23, No. 1, pp. 164–170. https://doi.org/10.1109/TPWRD.2007.911001

Anusha, V. S., Nithya, G., & Rao, S. N. 2017. *Comparative analysis of wireless technology options for rural connectivity*. pp. 402–407. https://doi.org/10.1109/IACC.2017.0090

Anushree, G., Chintan, P., Nadeem, M., & Tushar, P. 2014. Broadband over power lines: Internet everywhere. *International Journal of Scientific & Engineering Research*, Vol. 10, pp. 1018–1022.

Araújo, M., Ekenberg, L., & Confraria, J. 2019. *Satellite backhaul for macro-cells, as an alternative to optical fibre, to close the digital divide*. pp. 1–6. https://doi.org/10.1109/WCNC.2019.8885759

Bai, T., Zhang, H., Wang, J., Xu, C., Elkashlan, M., Nallanathan, A., & Hanzo, L. 2020. Fifty years of noise modeling and mitigation in power-line communications. *IEEE Communications Surveys & Tutorials*, Vol. 23, No. 1, pp. 41–69. https://doi.org/10.1109/COMST.2020.3033748

Bovberg, J. 2016. Overcoming Backhaul Challenges. *Fierece Wiereless*.

Broadband Commission. 2022. *The State of Broadband: Accelerating broadband for new realities* (p. 107). https://www.broadbandcommission.org/publication/state-of-broadband-2022/

Casier, K. 2010. Techno-economics of FTTH deployment in the presence of competition. *PhD Dissertation, Gent University*.

Chai, S. Y. W., Phang, F. J. F., Yeo, L. S., & How, B. S. 2022. Future era of techno-economic analysis: Insights from Review. *Frontiers in Sustainability*, Vol. 70. https://doi.org/10.3389/frsus.2022.924047

Chelangat, F. 2018. *Power line communication impedance profiling and matching for broadband applications*. https://ukzn-dspace.ukzn.ac.za/bitstream/handle/10413/18498/Chelangat_Florence_2018.pdf?sequence=1&isAllowed=y

Chiha, A., Van der Wee, M., Colle, D., & Verbrugge, S. 2020. Techno-economic viability of integrating satellite communication in 4G networks to bridge the broadband digital divide. *Telecommunications Policy*, Vol. 44, No. 3, 101874. https://doi.org/10.1016/j.telpol.2019.101874

Connected Society. 2016. *Connected Society Unlocking Rural Coverage: Enablers for commercially sustainable mobile network expansion*. GSMA. https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2016/07/Unlocking-Rural-Coverage-enablers-for-commercially-sustainable-mobile-network-expansion_English.pdf

Cruz, G., Touchard, G., Buckwell, M., & Liberatore, F. 2018. Enabling rural coverage: Regulatory and policy recommendations to foster mobile broadband coverage in developing countries. *GSMA, London, UK, Rep*.

Debita, G., Habrych, M., Tomczyk, A., Miedzinski, B., & Wandzio, J. 2019. Implementing BPL transmission in MV cable network effectively. *Elektronika Ir Elektrotechnika*, Vol. 25, No. 1, pp. 59–65. http://dx.doi.org/10.5755/j01.eie.25.1.22737

del Portillo, I., Eiskowitz, S., Crawley, E. F., & Cameron, B. G. 2021. Connecting the other half: Exploring options for the 50% of the population unconnected to the internet. *Telecommunications Policy*, Vol. 45, No. 3, 102092. https://doi.org/10.1016/j.telpol.2020.102092

Eichengreen, B., Simpson-Bell, C., & Arslanalp, S. 2022. Dollar Dominance and the Rise of Non-traditional Reserve Currencies. *IMF Blog*. https://www.imf.org/en/Blogs/Articles/2022/06/01/blog-dollar-dominance-and-the-rise-of-nontraditional-reserve-currencies

Farias, F., Fiorani, M., Tombaz, S., Mahloo, M., Wosinska, L., Costa, J. C., & Monti, P. 2016. Cost-and energy-efficient backhaul options for heterogeneous mobile network deployments. *Photonic Network Communications*, Vol. 32, No. 3, pp. 422–437. https://doi.org/10.1007/s11107-016-0676-6

GSMA. 2018. *The growing importance of mobile backhaul—From now until 2025*. GSMA. https://www.gsma.com/spectrum/wp-content/uploads/2019/02/Mobile-Backhaul-Options-InfoG.pdf

GSMA. 2021. *The State of Mobile Internet Connectivity 2021* (p. 66). https://www.gsma.com/r/wp-content/uploads/2021/09/The-State-of-Mobile-Internet-Connectivity-Report-2021.pdf

Hansryd, J., Edstam, J., Olsson, B.-E., & Larsson, C. 2014. Non-line-of-sight microwave backhaul for small cells. *Celebrating 90 Years of Technology Insights*, 12.

Hossain, M. B., Rahman, M. T., Asif, O., Rahman, M. A., & Chowdhury, M. E. 2014. Broadband over power line (BPL): An emerging technology for Bangladesh. *International Journal of Communications, Network and System Sciences*, *2014*. http://www.scirp.org/journal/PaperInformation.aspx?PaperID=49419

ITU. 2003. *The Birth of Broadband*. https://www.itu.int/newsarchive/press_releases/2003/factsheet.html

ITU. 2017. *LS/o/r on definition for broadband access (reply to SCV-LS013) [to SCV-CCV]*. ITU. https://www.itu.int/en/ITU-T/committees/scv/Documents/SCV-TD66.pdf

ITU. 2021. *Telecommunications/ICTs for rural and remote areas: Output Report on ITU-D Question 5/1 for the study period 2018-2021* (p. 106). ITU. https://www.itu.int/dms_pub/itu-d/opb/stg/D-STG-SG01.05.1-2021-PDF-E.pdf

ITU. 2022. *Global Connectivity Report 2022* (p. 186). International Telecommunication Union. https://www.itu.int/dms_pub/itu-d/opb/ind/d-ind-global.01-2022-pdf-e.pdf

Kalula, S., Ally, M., & Yonah, Z. 2022. Analysis of Factors for the Uncorrelated Relationship between the Broadband Internet Initiatives against Broadband Adoption for Rural Areas in Low and Middle-Income Countries: A Case of Tanzania. *International Journal of Advances in Scientific Research and Engineering*, Vol. 8, No. 1, pp. 27–38. https://doi.org/10.31695/IJASRE.2022.8.1.4

Katz, R., & Callorda, F. 2018. *The economic contribution of broadband, digitization and ICT regulation. International Telecommunication Union, published in Switzerland*. https://www.itu.int/dms_pub/itu-d/opb/pref/D-PREF-EF.BDT_AFR-2019-PDF-E.pdf

Kobos, P., Drennen, T., Outkin, A., Webb, E., Paap, S., & Wiryadinata, S. 2020. *Techno-Economic Analysis: Best Practices and Assessment Tools* (SAND--2020-13473, 1738878, 692989; p. SAND--2020-13473, 1738878, 692989). https://doi.org/10.2172/1738878

Kolydakis, N., & Tomkos, I. 2014. *A techno-economic evaluation of different strategies for front-/back-hauling of mobile traffic: Wireless versus fiber based solutions*. pp. 1–4. https://doi.org/10.1109/ICTON.2014.6876350

Kouchaki, M. R., & Dabibi, M. 2020. *Experiment on High Capacity Backhaul Transmission Link Aggregation Solution for 5G Networks*. 1–6. https://doi.org/10.23919/FRUCT48808.2020.9087444

Krizanovic Cik, V., Zagar, D., & Grgic, K. 2018. A framework for optimal techno-economic assessment of broadband access solutions and digital inclusion of rural population in global information society. *Universal Access in the Information Society*, Vol. 17, No. 3, pp. 517–540. https://doi.org/10.1007/s10209-017-0560-x

Kumar, S. K. A., Ihita, G. V., Chaudhari, S., & Arumugam, P. 2022. *A survey on rural internet connectivity in India*. 911–916. https://doi.org/10.1109/COMSNETS53615.2022.9668358

Lythreatis, S., Singh, S. K., & El-Kassar, A.-N. 2021. The digital divide: A review and future research agenda. *Technological Forecasting and Social Change*, 121359. https://doi.org/10.1016/j.techfore.2021.121359

Mahloo, M., Monti, P., Chen, J., & Wosinska, L. 2014. *Cost modeling of backhaul for mobile networks*. pp. 397–402. https://doi.org/10.1109/ICCW.2014.6881230

Mahmood, S. H., & Salih, A. M. 2019. Study of the most important factors affecting on efficiency of power line communication systems. *Journal of Engineering and Sustainable Development*, Vol. 23, No. 5, pp. 55–70. https://doi.org/10.31272/jeasd.23.5.5

Mahmood, S. H., Salih, A. M., & Khalil, M. I. 2019. *Broadband services on power line communication systems: A review*. 465–470. https://doi.org/10.1109/CSCS.2019.00085

Makamba, J. 2022. *Hotuba ya Waziri wa Nishati Mhe. January Y. Makamba Katika Bunge la Bajeti 2022/23*. Budget Speech, Dodoma, Tanzania. https://parliament.go.tz/uploads/budgetspeeches/1654099568-document%20(27).pdf

Marcus, A., & Wong, A. 2016. *Internet for All: A Framework for Accelerating Internet Access and Adoption*. 4–5.

Melhem, S. 2016. *Harnessing the internet for development*. https://documents1.worldbank.org/curated/en/326141637744735436/pdf/Harnessing-the-Internet-for-Development.pdf

NBS. 2022. *2022 Population and Housing Census*. https://www.nbs.go.tz/nbs/takwimu/Census2022/matokeomwanzooktoba2022.pdf

NICTBB. 2022. *National ICT Broadband Backbone Map* [Map]. NICTBB. http://www.nictbb.co.tz/map.php

Oughton, E. J., Comini, N., Foster, V., & Hall, J. W. 2022. Policy choices can help keep 4G and 5G universal broadband affordable. *Technological Forecasting and Social Change*, Vol. 176, 121409. https://doi.org/10.1016/j.techfore.2021.121409

Oughton, E., & Lehr, W. 2021. Next-G Wireless: Learning from 5G Techno-Economics to Inform Next Generation Wireless Technologies. *Available at SSRN 3898099*. https://dx.doi.org/10.2139/ssrn.3898099

Prieto-Egido, I., Valladares, J. A., Muñoz, O., Bernuy, C. C., Simo-Reigadas, J., Quispetupa, D. A., Fernández, A. B., & Martinez-Fernandez, A. 2020. Small rural operators' techno-economic analysis to bring mobile services to isolated communities: The case of Peru Amazon rainforest. *Telecommunications Policy*, Vol. 44, No. 10, 102039. https://doi.org/10.1016/j.telpol.2020.102039

RIA. 2017. *Research ICT Africa: Beyond Access Survey*. SADC. https://www.africaportal.org/documents/17652/2017_Policy_Brief_6_SADC.pdf

Saeed, A. M., & Masakure, O. 2016. The paradox of broadband access in sub-Saharan Africa. In *Africa in the Age of Globalisation* (pp. 113–130). Routledge.

Saunders, J., & Marshall, N. 2018. *Mobile backhaul options -Spectrum analysis and recommendations*. ABI Research.

Sharma, T., Chehri, A., & Fortier, P. 2021. Review of optical and wireless backhaul networks and emerging trends of next generation 5G and 6G technologies. *Transactions on Emerging Telecommunications Technologies*, Vol. 32, No. 3, e4155. https://doi.org/10.1002/ett.4155

Shrestha, D. 2019. *Impulsive noise cancellation and channel estimation in power line communication systems*. https://upcommons.upc.edu/bitstream/handle/2117/168868/TDS1de1.pdf?sequence=1&isAllowed=y

Slacik, J., Mlynek, P., Rusz, M., Musil, P., Benesl, L., & Ptacek, M. 2021. Broadband power line communication for integration of energy sensors within a smart city ecosystem. *Sensors*, Vol. 21, No. 10, 3402. https://doi.org/10.3390/s21103402

TCRA. 2021. *TCRA Telecommunications Quarterly report 2021*. https://www.tcra.go.tz/uploads/text-editor/files/Communications%20Statistics%20December%202021_1643809069.pdf

Thakur, K. K. 2018. Broadband Internet and Access Technology for Rural Connectivity. *BSNL, Akgec. Ac. In*. https://www.akgec.ac.in/wp-content/uploads/2019/06/2_KISHORE-Kumar-Thakur_Broadband-Internet-and-Access-Technology-for-Rural-Connectivity.pdf

Tjoa, A. M., & Tjoa, S. 2016. *The role of ICT to achieve the UN Sustainable Development Goals (SDG)*. pp. 3–13. https://doi.org/10.1007/978-3-319-44447-5_1

Webb, M. 2015. *Rural solution options for governments in emerging markets to increase broadband coverage in unserved and underserved rural areas*. Webb Henderson. https://www.vodafone.com/sites/default/files/2020-09/rural-solution-options-webb-henderson.pdf

World Bank. 2018. *World Bank Data on Population in Tanzania*. https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?locations=TZ

World Bank Group. 2016. *World development report 2016: Digital dividends*. World Bank Publications.

Wu, J., Guo, S., Huang, H., Liu, W., & Xiang, Y. 2018. Information and communications technologies for sustainable development goals: State-of-the-art, needs and perspectives. *IEEE Communications Surveys & Tutorials*, Vol. 20, No. 3, pp. 2389–2406. https://doi.org/10.1109/COMST.2018.2812301

Zeydan, E., Dedeoglu, O., & Turk, Y. 2021. Performance monitoring and evaluation of FTTx networks for 5G backhauling. *Telecommunication Systems*, Vol. 77, No. 2, pp. 399–412. https://doi.org/10.1007/s11235-021-00767-0

Zimmermann, M., & Dostert, K. 2002. A multipath model for the Powerline channel. *IEEE Transactions on Communications*, Vol. 50, No. 4, pp. 553–559. https://doi.org/10.1109/26.996069

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