Tanzania Journal of Science 48(2): 245-255, 2022
ISSN 0856-1761, e-ISSN 2507-7961

Impact of Radio Operating Environments on Broadband Connectivity

Libe V Massawe* and Peter J Chitamu
Department of Electronics and Telecommunications Engineering, College of Information and Communications Technologies, University of Dar es Salaam, P. O. Box 33335, Dar es Salaam, Tanzania
*E-mails: *liebetz@yahoo.co.uk, pjchitamu@yahoo.com*
**Corresponding author*
Received 14 Feb 2022, Revised 25 Apr 2022, Accepted 7 May 2022, Published Jun 2022
DOI: https://dx.doi.org/10.4314/tjs.v48i2.2

Abstract

Broadband connectivity and services commonly referred to as the Internet is the key enabling facility for the modern digital economy and the driver for the Fourth Industrial Revolution (4IR or Industry 4.0). In Tanzania, there are over 49% Internet subscriptions for mobile broadband services using 3G UMTS and 4G standards infrastructure, which are predominantly available in urban areas. The non-urban areas remain mostly 2G coverage areas and lack mobile broadband connectivity and services. Transforming existing 2G mobile networks to broadband infrastructure can be achieved by swapping 2G sites with 3G or 4G sites or incrementally replacing 2G sites with 3G or 4G sites on demand. In this work, we investigated the performance of the UMTS family of standards to deliver broadband connectivity and services outside major towns and cities in three different radio operating environments, namely hilly, undulating and flat terrain landscapes. Results show that the achievable 3G data rate deteriorates depending on the type of operating environment as the internet user moves away from the base station. Therefore, mobile broadband deployment in non-urban areas is not simply replacement of 2G sites for 3G sites; it will require special deployment strategies to achieve a total broadband coverage.

Keywords: Internet Services; Mobile Broadband; Radio Channel Modelling; Telecoms Industry Innovation; Sustainable Infrastructure Development.

Introduction

Tanzania is characterised by low population densities in many areas which make deployment of mobile broadband infrastructure to be much more expensive outside cities and major towns in terms of costs, both operational costs (OPEX) and capital expenditure (CAPEX) per connected broadband subscriber (Chitamu and Chen 2001). This is reflected in the digital divide between urban and non-urban areas in terms of broadband connectivity and services.

There are two approaches to achieve 100% population coverage for mobile broadband infrastructure: First is to swap out all 2G sites and backhaul networks with mixture of 3G and 4G or just 4G sites, and secondly is to incrementally upgrade the 2G network to 3G and 4G networks for broadband connectivity and services as the market forces dictate (ITU 2005, Byanyuma and Zaipuna 2017, Pazi 2019). While the first approach is adopted in urban areas, the high investment and operational costs for mobile broadband infrastructure makes this approach unattractive for rural areas. The second approach which was also recommended by ITU (2005) as the more cost-effective solution for rural areas, the existing 2G network sites at 900 MHz band are re-used and upgraded to 3G UMTS network to offer mobile broadband services.

According to TCRA Telecom Statistics shown in Figure 1, by December 2020 the voice subscriptions were 89%, while internet subscriptions were at 49% (TCRA 2020). There is a subscription gap of almost 40% between voice and internet services. The difference between voice and internet tele-densities is not surprising. It is much more expensive to deploy infrastructure for broadband internet services compared to narrowband voice services, more than 10 times increase in cost in low density areas (Chitamu 2012). With the Tanzania government desire to increase internet subscriptions to 80% by 2025, the key challenges to make this happen have to be investigated and thoroughly understood.

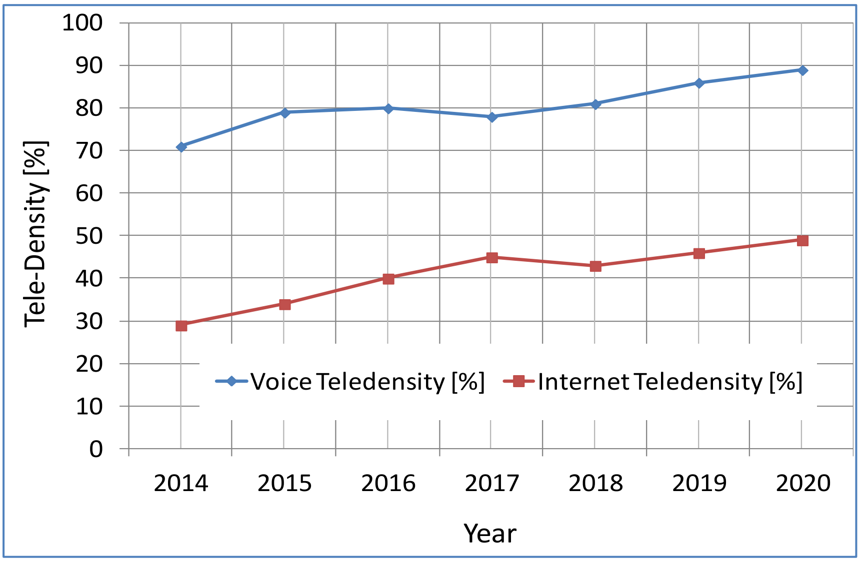

Figure 1: Tanzania Voice and Internet Tele-density 2014 to 2020 (TCRA 2020).

The purpose of the investigation reported in this paper was to find out the achievable mobile broadband coverage per cell site taking into consideration the data rate target of 2 Mbps [National ICT Policy 2016] at the cell edge and hence its implications on mobile broadband population coverage using the different members of the 3G UMTS family of standards. The results take into account three canonical areas of hilly terrain, undulating landscape and flat terrain areas in the underserved and rural areas of Tanzania.

Literature survey

This work focuses on broadband subscription numbers and hence the infrastructure to support the users. The rural vs urban population digital divide in Tanzania is reflected in the current voice and internet subscriptions (Figure 1) versus the target of 80% internet subscriptions that the government would like to see by 2025.

Projections from 2012 National Census, the rural areas have a population of nearly 42 Mil residing in over 18,500 villages (NBS 2012). However, most of them reside in low population density areas ranging from 50 to 500 people per sq.km. To provide them with mobile broadband connectivity requires deployment of large macro-cellular coverage sites so as to make the business case commercially viable. However, as you increase the coverage area per site the radio becomes more susceptible to Inter-Symbol Interference (ISI) from multipath propagation induced fading which limits both coverage and effective data rates of the radio link. Table 1 shows various numbers of interests.

Table 1: Rural broadband market opportunity

	Description	%	Numbers [Mil]	Comments
1	Tanzania population	100	60	Projections 2021
	Urban	30	18	Broadband internet population coverage
	Rural	70	42	No or limited broadband access
2	Voice subscriptions	89	53.4	Multiple SIM subscriptions not considered
3	Internet subscriptions	49	29.4	Mainly in urban areas, Multiple SIM Subs not considered
4	Rural broadband addressable market	10	4.2	5 to 15% of population
5	Target subscriptions	80	48	Government target by 2025
6	Current unique broadband subscriptions	37	22.2	Estimate 27% [ITU]
7	Deficit in today's figures	43	25.8	New Internet subscriptions in 2022 to 2025

From Table 1, it was noted that, with internet subscription of 49% and taking into account multiple SIM card subscriptions, nearly all internet subscriptions are in the urban areas. The broadband market opportunities in rural areas are great but not straightforward due to the barriers of connecting the unconnected (ITU 2020, GSMA 2020). This investigation assumes the rural broadband market opportunity to be 10% of the rural population based on the difference between urban and rural household income and expenditure (NBS 2019). From the estimates in Table 1, about 26 Mil new broadband subscriptions are needed to meet the target of 80% subscriptions of 48 Mil by 2025, which is an annual growth rate of 22% as shown in Table 2. These are big broadband subscription numbers to come from sparsely populated areas on one hand and using 3G UMTS on the other.

Table 2: New broadband subscriptions for a target 80% subscriptions

Year	2021	2022	2023	2024	2025
Subscriptions	22,200,000	27,084,000	33,042,480	40,311,826	49,180,427

Mobile networks are used to support over 98% of users in Tanzania, and now the broadband version, Mobile Broadband Networks will as well be the dominant infrastructure for internet users in Tanzania (TCRA 2020). Operators in Tanzania have deployed mainly the 3G UMTS family of standards (Pazi 2019), namely WCDMA, 3G UMTS Releases 4, 5, 6 and 7, with their specifications as shown in Table 3. When using a mobile phone in Tanzania you will notice it indicating the type of networks in use that include 2G, E, 3G, H and H+ networks which are UMTS family of mobile network standards standardized by 3GPP.

In Table 3, 4G LTE Release 8 and 10 are added for reference purposes since operators have also deployed 4G LTE in the country but the mobile broadband subscription numbers are currently coming mostly from 3G UMTS because of their symbiotic relationship with 2G GSM network. With 3G UMTS family the problem is as follows: The advertised data rates like 28 Mbps for HSPA+ are not what the users will experience in practice because of a number of reasons, including the following:

i. The overheads in the radio bearers will reduce the effective throughput to around 60%, of the advertised rates; let us say from 28 Mbps down to 17 Mbps.
ii. The downlink is shared, so the single user throughput will depend on the number of concurrent users at any particular time. If

there are no channel impairments and for a single user data rate of 2 Mbps, this capacity will serve about 8 concurrent users with a bit more considering data switching characteristics and packet statistical multiplexing (i.e. overbooking).

iii. The radio operating environment will further determine the received signal strength at the user handset at any particular location which in turn will determine the achievable single user data rates.

Table 3: Network KPIs for 3G UMTS family of standards

	WCDMA (UMTS)	HSPA HSDPA/ HSUPA	HSPA+	LTE	LTE Advanced (IMT Advanced)
Max downlink speed bps	384 k	14 M	28 M	100 M	1 G
Max uplink speed bps	384 k	5.7 M	11 M	50 M	500 M
Latency round trip time approx	150 ms	100 ms	50 ms (max)	10 ms	≤ 5 ms
3GPP Releases	Rel 99/4	Rel 5/6	Rel 7	Rel 8	Rel 10
Approx years of initial roll out	2003/4	2005/6 HSDPA 2007/8 HSUPA	2008/ 2009	2009/10	2014/15
Access methodology	CDMA	CDMA	CDMA	OFDMA/ SC-FDMA	OFDMA/SC-FDMA

The different 3G UMTS radios are very similar using WCDMA with 5 MHz channel spacing and a 3.84 Mcps Direct Signal Spread Spectrum (DSSS) signal with differences in source and channel coding schemes to meet different data rates on the radio bearers. Out of the 3G UMTS networks (R99, R4, R5, R6 and R7), only Release 6 (HSPA) and Release 7 (HSPA+) with their UL/DL data rates of 14/5.7 Mbps and 28/11 Mbps, respectively can be considered to meet the minimum requirements for mobile broadband network with download single user data rates of 2 Mbps.

The challenge in mobile broadband is how to deal with the radio channel variability while maintaining broadband connectivity. The operating environments create random stochastic radio channel processes and hence cause the random channel variability. Consequently, the received radio signals vary randomly and have direct dependence on the operating environments: terrain, morphology, land use, and other natural and manmade obstacles within the radio propagation environments between the base station and the user handset (Chitamu and Braithwaite 1996, Chitamu and Mgombelo 1998).

According to the 2012 National Census, the Tanzania average population density was 52 people per sq.km (NBS 2012) and according to the National ICT Policy of 2016 (NICT 2016) broadband is defined as a connection of at least 2 Mbps. This is the benchmark for our investigation.

Table 4 shows the estimated internet (mobile broadband) addressable market for areas with population densities from 50 to 1,000 people per sq.km considering three different coverage areas with cell radius of 1 km, 3 km and 5 km and a market penetration of 10% assuming a market share of 100% calculated using Equation 1. For example, in an area with a population density of 100 people per sq.km and network coverage of 3 km it is expected to have an addressable market of only 283 from total population coverage of 2,830. The numbers increase to 785 if the network population coverage for broadband reaches 5 km. If active users generate average revenue per user (ARPU) of US$ 3, then the sites will earn average monthly revenue of US$ 849 and US$ 2,355 for the 3 km and 5 km radius areas, respectively against huge capital investments. In the telecoms business subscription numbers count for everything and numbers are achieved by providing network population coverage.

$$AddrMarket = PoplnDensity * Area * Penetration * MarketShare \quad (1)$$

Table 4: Internet addressable market based on population densities and 10% penetration

Population density	Coverage radius [km] 1	3	5
50	16	141	393
100	31	283	785
200	63	565	1,571
500	157	1,414	3,927
1000	314	2,827	7,854

From business profitability considerations, a large number of subscribers per BTS is needed. In low population density areas, this can be obtained by providing large coverage area per BTS/cell. This is the coverage limited scenario that is addressed in this paper. In cities like Dar es Salaam with high population density of over 3,000 people per sq.km, a small area will have a very large number of potential internet users because of the high population densities. This is designated as capacity limited network design concept, which is the opposite of rural areas scenario.

Materials and Methods

The achievable data rates are analysed in different propagation environments or canonical areas based on propagation measurements carried out in different parts of Tanzania and considering 3G UMTS networks Releases 4, 5, 6 and 7 operating in the 900 MHz band. The analysis considers a transmit power of 40 dBm and cell edge range limited by data rate rather than normal receiver sensitivities on the downlink (BTS to MS). The BTS is assumed to have a height of 20 m and the user at 1.5 m. Furthermore, the downlink is considered because this is where the high broadband data rates are more critically needed.

The broadband radio channel is considered from both pathloss and multipath propagation characteristics. The pathloss models used in this investigation are based on results from propagation measurements carried out in different parts of Tanzania by Chitamu and Braithwaite (1996).

In general, the received signal power at different distances from the transmitter to the receiver will be falling off with distance as illustrated in Figure 2 due to both pathloss and impacts from multipath fading at the background of Additive White Gaussian Noise (AWGN) and other interferences. The impact is measured by analysing the figure of merit E_B/N_O at any particular location on the link, thus giving a radio link power budget. However, in terms of coverage, the cell-edge radius will depend on the type of service being considered as services have different characteristics and requirements from the network as illustrated in Figure 2.

The received signal power in dB is linear with log-distance falling off with a gradient equal to the pathloss exponent. This is derived as shown in Equations 2.

$$P_r \propto P_T \frac{1}{d^n} = KP_T \frac{1}{d^n} \qquad 2(a)$$

In dB representation, Equation 2(a) becomes:

$$P_r = 10log_{10}(KP_T) - 10nlog_{10}(d) \qquad 2(b)$$

where Pr is the received power, P_T is the transmit power, n is the pathloss exponent, d is the distance between the transmitter and receiver and K is a proportionality constant determined from propagation measurements for a given canonical area. Equation 2(b) is a line with gradient – 10n.

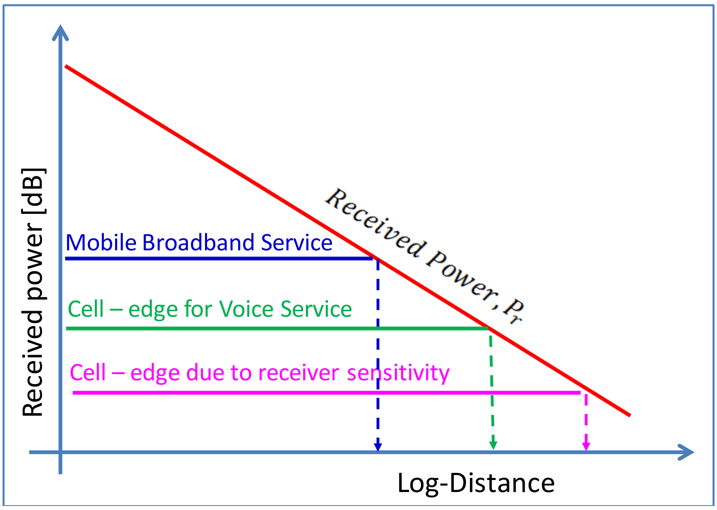

Figure 2: Illustration of link budget using different network design concept.

For any service like voice or internet (data), the network figure of merit E_b/N_O for digital systems and S/N for analogue systems reduces with distance because it depends on the received signal power that reduces with distance as you go away from the transmitter. However, each service (e.g. voice) has a specific value for E_b/N_O or S/N and the corresponding network Key Performance Indicators (KPIs) for which any value below the specific value the network and service will not work satisfactorily. The received signal strength (RSSI) indicated as bars on the user handsets is one such network KPI. Others include achievable data rates, capacity and network delay and delay variation. If there is a single bar on the phone RSSI, it might be difficult to make an internet voice or video calls (e.g. using WhatsApp). Table 5 shows typical network KPIs for voice and internet services from where some of the key differences between voice centric and data centric networks deployments can be noted.

Table 5: Selected network KPIs for 2G and 3G mobile networks

	Network KPI	Voice centric network	Data centric network
1	Mobility level	Full mobile	Portable, pedestrian
2	Bit Error Rate (BER)	Error tolerant, 10^{-3}	Error intolerant, 10^{-5}
3	Single user data rates	10 kbps	2 Mbps
4	Convergence of services	1 Dimension, narrowband services	Multidimensional broadband Converged services, use cases
5	Radio channel characteristics	Not affected much by multipath, limited ISI	Severely impacted by multipath hence migrations from 2G, 3G, 4G and now 5G
6	Backhaul requirements	Typically 2 to 3 E1s (6 Mbps) per BTS	Typically 20 to 30 E1s for 3G and 80 to 100 E1s for 4G
7	BTS interfaces	TDM, E1s (PDH & SDH), hierarchical network topology	IP or IP over TDM providing scalable and distributed connectivity
8	Example networks	2G GSM	3G UMTS

For digital systems, the value of E_b/N_O corresponds to a Bit Error Rate (BER) target value depending on the modulation and coding scheme used. For example, voice and video streaming services can work well at a BER of 10^{-3} and are normally referred to as error tolerant services. However, data services work at much lower BER of about 10^{-5} and are referred to as error intolerant services (Kapov et al. 2004). Hence having fixed BER target based on the type of services to be offered then automatically both E_b/N_O and the network type are selected to meet the required coverage and data rate performances for broadband connectivity. Pathloss in general limits the range of a communication link because it reduces the received signal power and consequently the E_b/N_O and the achievable link data rates.

In mobile environment, a wireless channel will exhibit random fading behaviour that can be modelled as either flat or frequency selective fading depending on the multipath delay spread relative to the radio link data rates. The mobile networks 2G GSM and 3G UMTS are designed with radios that are characterized by frequency selective fading and hence the main mitigations include equalization and RAKE receiver for 2G and 3G mobile networks, respectively.

In this investigation, the impact of the multipath delay spread and frequency selective fading is accounted for in the link budget by introducing a LogNormal shadowing and Rayleigh fading margins shown in Equation 3.

$$P_L(d) = P_L(d_O) + 10n\log_{10}\left(\frac{d}{d_O}\right) + \chi_\sigma[dB] \quad (3)$$

where d_o is the reference distance close to the transmitter, n is the pathloss exponent, d is distance from the transmitter to the receiver and χ_σ is the lognormal shadowing component. Since mobile broadband has limited mobility, that is pedestrian mobility level, the Rayleigh fading margin is ignored in the pathloss calculation in Equation 3. Now the received signal power P_r can be determined by using Equation 4 for the average received signal power.

$$P_r = P_T + G_T + G_r - P_L(d)[dB] \quad (4)$$

where P_r is the received power at distance d km from the transmitter, P_T is the transmitter power and G_T and G_r are the antenna gains at the transmitter and receiver, respectively. Embedded on P_r is the pathloss P_L(d) which is the only random variable process to influence the received power levels.

Equations 5, 6, and 7 represent large scale average pathloss from three different canonical areas of flat terrain like Ngudu in Mwanza, undulating landscape like in Njombe and Mafinga and hilly areas like in Amani, Lushoto, Moshi and Usa River (Chitamu and Braithwaite 1996). They have pathloss exponents as shown in Table 6.

Table 6: Pathloss exponents n for 3 canonical areas (Chitamu and Braithwaite 1996)

n	Terrain, environment	Examples
4.2	Flat terrain with light vegetation	Ngudu–Mwanza
5.3	Undulating landscape, with moderate vegetation	Nombe–Iringa
7.2	Hilly and heavily forested	Usa River–Arusha, Lushoto and Amani–Tanga

Based on propagation measurements and considering operating frequency in the 900 MHz band, the average pathloss in hilly and heavily forested terrain like Amani–Tanga, Lushoto, Usa River–Arusha and Kilimanjaro is given by Equation 5 (Chitamu and Braithwaite 1996).

$$P_L = 107 + 72\log_{10}d[dB] \quad (5)$$

For undulating landscape with light vegetation like Iringa, Dodoma, Morogoro and Njombe, the average pathloss is given by Equation 6 (Chitamu and Braithwaite 1996).

$$P_L = 101 + 53\log_{10}d[dB] \quad (6)$$

While for flat terrain with light vegetation like Ngudu–Mwanza the average pathloss is given by Equation 7 (Chitamu and Braithwaite 1996).

$$P_L = 95 + 42log_{10}d[dB] \qquad (7)$$

For free space (FS), the pathloss is calculated using Equation 8.

$$P_L = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi f d}{c}\right)^2 \qquad (8)$$

where f is the operating frequency, λ is the wavelength, c is the speed of light and d is the distance between the transmitter and receiver.

The received signal power P_r has to be greater than the receiver threshold level of about -80 dBm for broadband services or its equivalent E_b/N_O for a BER of 10^{-5}. A relationship between the figure of merit E_b/N_O and the data rate is established using Equation 9.

$$\frac{E_b}{N_O} = \frac{P_r}{N_O R_b} \qquad (9)$$

where E_b is energy per bit, N_O is noise power spectral density, P_r is the received signal power and R_b is the link data rate. The energy per bit E_b is inversely proportional to the data rate, hence increasing the data rate decreases E_b resulting in increased BER. The N_O is defined as shown in Equation 10.

$$N_O = kT \qquad (10)$$

where k is Boltzmann's constant and T is the Kelvin temperature. The typical value for N_O in mobile networks is –163 dBm / Hz.

Therefore, using the system parameters P_T, G_T and G_r, the received signal power P_r is calculated at different distances from the BTS in different operating environments using Equation 4 while substituting P_L from Equations 5, 6, 7 and 8 for different canonical areas. For the coverage limited case, both the received signal power and the achievable data rates are determined using Equation 11. Using Equation 11(c), the relationship between the received signal strength P_r and the data rate R for a particular network is established for a given target figure of merit E_b/N_O and hence the coverage to meet the broadband connection defined as 2 Mbps can be planned accordingly.

$$\frac{E_b}{N_O} = \frac{\frac{P_r}{R}}{\frac{N}{W}} = \frac{P_r W}{NR} = \frac{P_r}{N_O}\frac{1}{R} \qquad (11a)$$

$$R = \frac{P_r}{N_O}\frac{1}{\frac{E_b}{N_O}} \qquad (11b)$$

$$P_r = \frac{E_b}{N_O} N_O R \qquad (11c)$$

where E_b/N_o is the receiver figure of merit in digital communications networks, Pr is the received signal power, N_O is noise power spectral density and R is data rate at the receiver. Equation 11 shows the relationships and tradeoffs between the figure of merit E_b/N_O , the received signal power P_r, the noise power spectral density N_O and the data rate R at the receiver. The pathloss between the receiver and transmitter is embedded on the received signal power Pr and the achievable link data rate at the receiver R for a given figure of merit E_b/N_o or BER level is calculated using Equation 11(b). As you go away from the transmitter (BTS), the received signal strength Pr reduces and correspondingly the ability of the link to support high speed communications also reduces as well in proportion to distance to the pathloss exponent d^n. Since it is an exponential relationship between Pr and pathloss, minor changes in operating environments can result in big swings in both coverage and achievable data rates.

Results

First, the pattern of the received signal strength Pr in Equation 4 corresponding to the different canonical areas (Equations 5, 6, 7 and 8) with G_T and G_r set equal to 0 dBi for normalization purposes and P_T of 40 dBm are shown in Figure 3. The voice threshold is set at -90 dBm and the data threshold is set at -80 dBm to correspond to BER of 10^{-3} and 10^{-5}, respectively.

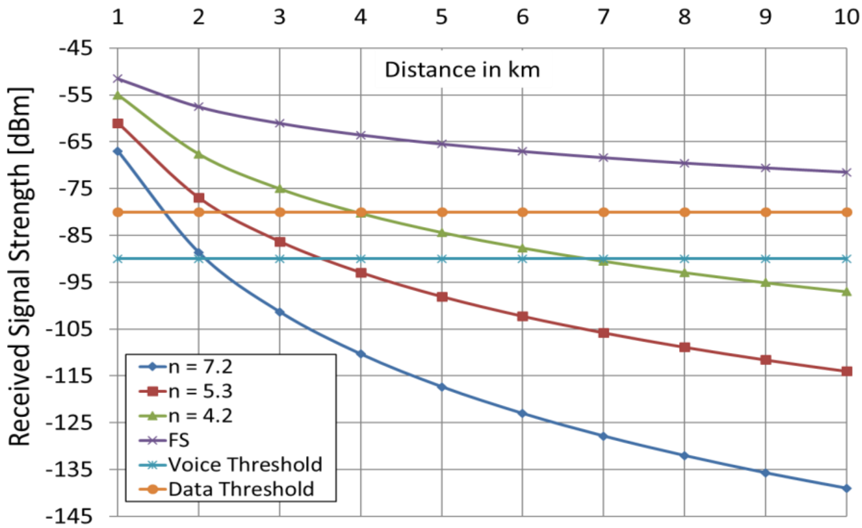

Figure 3: Received signal powers in different operating environments.

The FS curve shows received signal power in Free Space scenario at 900 MHz. Based on the BER requirements, the thresholds for the received signal power to support internet or broadband and voice services are –80 dBm and –90 dBm respectively. It is noted that for the hilly terrain case, the coverage range for internet is substantially reduced to about 1.5 km compared to the flat terrain case where the coverage is 4 km. There is no coverage problem for the line of sight (LOS) Free Space propagation case. The reduced received signal power is what determines the achievable data rate using Equation 11(b). The pathloss patterns only depend on the operating environments, the operating frequency of 900 MHz and the height of the antennas that for this case are assumed to be 20 m at the transmitter and 1.5 m at the receiver.

Figure 4 shows that the achievable data rate deteriorates very quickly with distance but more so in hilly areas where multipath propagation with excessive delays is more prevalent. This is because the received signal strength falls off to the exponent of the distance n = 4.2 in flat terrain, n = 5.3 in undulating landscape and n = 7.2 in very hilly areas as shown in Table 6 above.

A huge difference is noted on achievable data rates between Free Space (FS) and hilly terrain (n = 7.2). As a result, the working distance is limited to less than 1 km range for hilly and undulating terrain operating environments. This means these vulnerable areas require more efforts and innovations in network planning and deployment strategies.

It is noted from Figure 3 that in Free Space environment coverage is more than 10 km. However, as you go from flat terrain (n = 4.2), to undulating landscape (n = 5.3) and hilly areas (n = 7.2), the coverage ranges for broadband are 4 km, 2.1 km and 1.5 km, respectively, while for voice they are 7 km, 3.5 km and 2 km, respectively.

For the UMTS family of standards, the best scenario is obtained when using HSPA+ with its peak downlink data rate of 28 Mbps. This is used as the reference network for performance comparisons. From Figure 4 it is noted that the achievable data rate in just below 14 Mbps at 1 km and 5.6 Mbps at 1.5 km in flat terrain areas with pathloss exponent n of 4.2. The data rates in undulating is about 2.8 Mbps at 1 km range but already below 2 Mbps in undulating and hilly terrains at 1.5 km. The network is therefore already very coverage limited. For HSPA Release 6, the situation is even worse as the baseline data rate is only half of that for HSPA+.

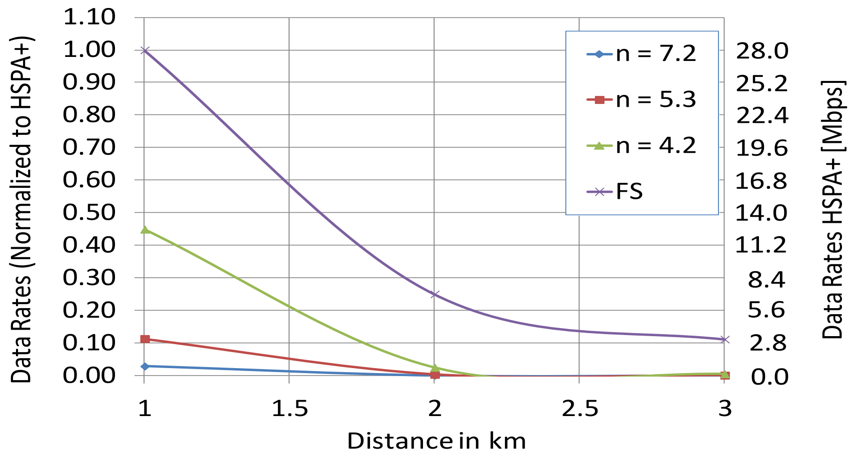

Figure 4: Impact of distance on broadband connection speed for HSPA+.

Discussions

The determination of the radio channel characteristics is very crucial in planning wireless networks in general and a broadband wireless network in particular. In hilly terrain, the broadband channel bandwidth can be reduced to a fraction of its line-of-sight conditions due to multipath fading, which also affects the link margin due to additional diffraction losses and multipath induced Inter-Symbol Interference (ISI). It is noted that with a broadband definition of 2 Mbps at the cell edge, only about 1.5 km cell radius can be achieved in hilly areas compared to about 4 km in flat terrain areas and over 10 km in Line-of-Sight conditions. Therefore, to achieve macrocellular broadband coverage in areas with low population densities, a lot of efforts and innovations need to be put in the planning and deployment strategies of the wireless broadband network. The focus should be deployment to avoid or limit the impacts of excessive multipath propagation such as using sectorized sites, modelling of deployment sites and use of small cells approach.

Table 1 shows that a large number of new broadband connections of at least 25.8 Mil are needed to meet the target of 80% broadband tele-density by 2025. These new connections or subscriptions have to come from the low population density areas that are more difficult to reach with mobile broadband coverage compared to urban areas. Therefore, more efforts and innovations are needed in the design, planning and deployment strategies of robust last mile broadband connections and their corresponding backhaul networks to support them in order to minimize the costs of broadband service provision outside cities and major towns.

Conclusions

Broadband connectivity is important for users to gain access to digital Contents, Apps and Services that can transform their livelihoods and improve their socio-economic conditions. The operating environments or canonical areas as referred to in this paper affect both the coverage and achievable data rates of mobile broadband networks at different locations within the coverage areas. The combination of low population densities and impacts from terrain and operating environments makes it difficult to deploy profitably 3G UMTS mobile broadband networks in rural areas of Tanzania. This is especially so if the deployment approach adopted is the traditional macrocellular coverage. It is noted that HSPA+ is the best option amongst the 3G UMTS family of standards for broadband connectivity and services in low density or rural operating environments at 900 MHz frequency band.

Innovations in mobile networks mitigations to overcome channel impairments are needed to be further investigated in the different canonical (operating) areas in order to extend the mobile broadband coverage especially in hilly and undulating types of operating environments. Adaptive modulation and coding (represented by the changing of networks from 2G, E, 3G, H and H+ on the user handset) that is extensively used to adjust data rates and other network KPIs to the prevailing radio conditions will not solve the problem because the baseline networks of HSPA and HSPA+ are already very coverage limited.

There are provisions in mobile broadband networks to improve the link budget and the achievable data rates beyond what is predicted in the results above. These include the use of multiple antennas (MIMO technology), increasing effective transmit powers, use of adaptive modulation, sectorization, adaptive coding, increasing antenna gains and increasing tower heights. If all these fail, then the next best option is to use 4G LTE which uses different radio technology to cope with impairments due to multipath induced fading and ISI in a completely different manner.

Acknowledgements

The authors would like to acknowledge the support from the members of the Wireless Communications Research Group at the Department of Electronics and Telecommunications Engineering of the College of Information and Communications Technologies, University of Dar es Salaam.

References

Byanyuma M and Zaipuna OY 2017 Overview of broadband connectivity for rural areas-Tanzania as a case study. *Int. J. Comput. Sci. Inf. Security* 15(4): 312-320.

Chitamu P 2012 Can Heterogeneous networks save us from traffic jams? Mobile Network Optimisation Africa 2012, Holiday Inn Sandton, Jo'Burg, South Africa.

Chitamu PJ and Braithwaite SJ 1996 Path loss prediction for a digital radio-telephone application in rural Tanzania at 300 MHz. Proceedings of IEEE Africon '96, 4th Africon Conf. in Africa, Stellenbosch, Rep. South Africa: 303-307.

Chitamu PJ and Chen PC 2001 Economic viability study of cellular network technologies for low density traffic areas. Proceedings of 3rd International Conference on Information (ICICS2001), Communications, and Signal Processing, Singapore.

Chitamu PJ and Mgombelo HR 1998 Propagation measurement results for scintillating channels from selected areas of rural Tanzania. Proc. of International Conf. on Advances in Systems, Signals, Control, and Computers (SSCC'98), Durban, South Africa: 425 – 430

GSMA 2020 The state of mobile internet connectivity report. www.gsma.com/connected-society

ITU 2005 Guidelines on the smooth transition of existing mobile networks to IMT 2000 for developing countries (GST).

ITU 2020 Broadband Commission, The State of Broadband: Tackling digital inequalities, A decade of action. www.itu.int/broadband

Kapov LS, Huljenic D, Mikic D, Vilendecic D 2004 Analysis of end-to-end QoS for networked virtual reality services in UMTS. *IEEE Communications Magazine* 42(4): 49-55

NBS 2012 Population and Housing Census General Report–Population in Wards, National Bureau of Statistics (NBS) www.nbs.go.tz

NBS 2019 Household Budget Survey 2017-18, Key Indicators Report. National Bureau of Statistics (NBS) www.nbs.go.tz

NICT 2016 Tanzania National ICT Policy 2016, National Bureau of Statistics (NBS) www.nbs.go.tz

Pazi SM 2019 Assessment of broadband access technologies in Tanzania rural areas. *Int. J. Internet of Things* 8(1): 1-9.

TCRA 2020 Telcom Stats December 2020, https://www.tcra.go.tz/statistic/2020 Quarterly Statistics Reports/December.