

Analysis of Powerline Channel Model for Communication from Primary Substation Node to End-Users

J. Anatory, N. H. Mvungi, and M. M. Kissaka

Abstract—The low voltage power networks in developing countries like Tanzania are designed without taking into consideration their application in data communication. In order to use them for data communication, powerline channel models have been developed and analysed in order to understand the factors that will affect the transmission. In this paper transfer characteristics of powerline channel from power users to primary substation have been modeled and analyzed. Simulation results show that the signal in PLC environment attenuates more with interconnections, which needs to be amplified/regenerated within a few meters.

Index Terms—Powerline communications, topology, multipath, channel characterization.

I. INTRODUCTION

Recently there is a growing interest in the use of powerline channel (PLC) for communication to non-urban and lowly populated areas. It is considered to be a viable technology for countries like Tanzania where powerline network infrastructure already covers very larger geographical areas. In order to be able to communicate through powerline channel various issues have to be addressed for quality and optimal communication. Communication in PLC is affected by various parameters such as noise, attenuation of the signal and operating frequency. In PLC, the length of the cable, number of branches and transmission frequency contribute to signal attenuation. These factors should be taken into consideration in a PLC system design.

The topology of the type of network under discussion is shown in figure 1. It consists of 4km of all aluminum conductor steel reinforced (AACSR) from the primary substation to a High Tension (HT) pole at the secondary substation. The link from HT pole to the secondary substation (distribution transformer) is a 20m long, 50mm², ACSR cable. A 100mm², 1.2 km all aluminum conductor (AAC) links the distribution transformer to customer pole. From customer pole to the bracket on customer house a 25 mm², 20m, AAC cable is used. The energy meter is connected to the bracket by a 16mm², 10m, PVC, AAC, cable. From this topology it can be seen that from the consumer energy meter to primary substation different cable sizes and different separation between cables are used which results into varying line parameters.

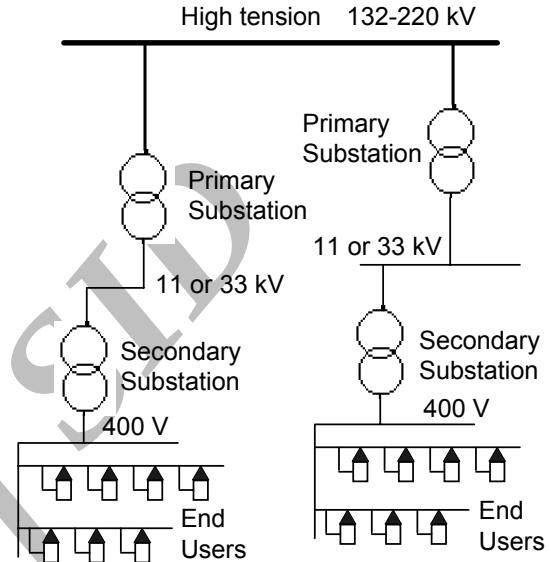


Fig 1: Topology of powerline distribution network.

The paper is organized as follows: section two describes the PLC transmission parameters from consumer energy meter to primary substation. Section three gives the general concept of multipath through PLC, while section four describes the propagation delay as it contributes to transfer function that consists of multi-path propagation due to a number of end users connected to the network. Section five analyses channel modeling dependence on distance, frequency and branched network, section six provides simulation results and conclusion is given in section seven.

II. PLC TRANSMISSION PARAMETERS

A. From Primary Substation to Customer Pole

The separation, D , between conductors for the PLC system from primary substation to customer bracket is much greater than the radius a of the conductors, hence the capacitance C , inductance L , and AC resistance R per loop meter are given by (1), (2) and (3) respectively [1], [2].

$$C = \frac{\pi\epsilon}{\cosh^{-1}(D/2a)} [F/m] \quad (1)$$

$$L = \frac{\mu}{\pi} \cosh^{-1}(D/2a) \quad (2)$$

The series resistance R of the conductor is given by (3).

$$R = 2 \left(\frac{R_s}{2\pi a} \right) = \frac{1}{\pi a} \sqrt{\frac{\pi f \mu_{Al}}{\sigma_{Al}}} [\Omega] \quad (3)$$

Manuscript received September 4, 2002; revised July 30, 2003.

The authors are with the Faculty of Electrical and Computer Systems Engineering, University of Dar es salaam, Tanzania (e-mail: anatory@engineer.com, mvungi@ee.udsm.ac.tz, kissaka@ee.udsm.ac.tz).

Publisher Item Identifier S 1682-0053(04)0173

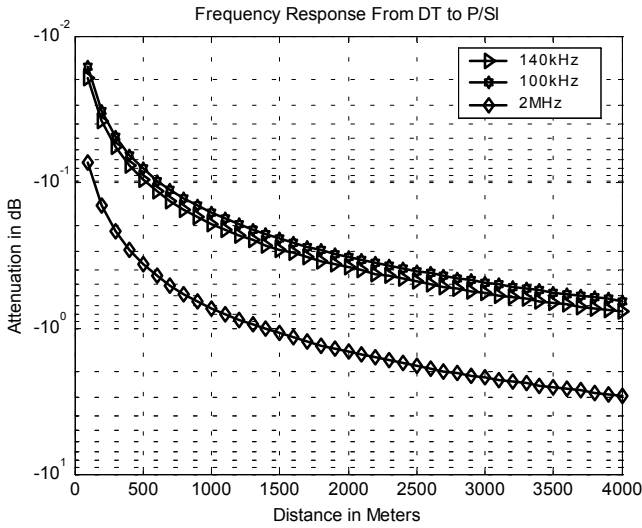


Fig. 2. Frequency response of Powerline cable from distribution transformers to primary substations at different frequencies.

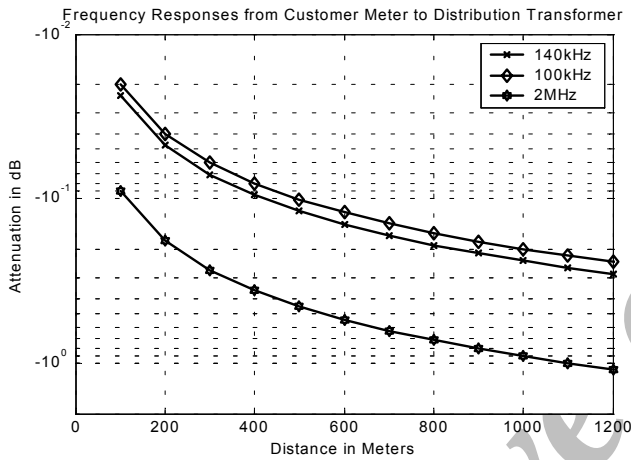


Fig. 3. Frequency response of powerline cable from power users to distribution transformers.

where the parameters μ_{Al} and σ_{Al} are permeability and conductivity of the aluminum conductors respectively. The propagation coefficient γ is given by (4)

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (4)$$

where α is the attenuation coefficient and β is phase is phase change coefficient. The attenuation function is given by (5), where the parameter l is the length of the cable.

$$A(f, l) = \exp(-\gamma l) \quad (5)$$

B. From Bracket to Customer Energy Meter

The power lines from customer pole to customer energy meter have separation d between wires less than the radius a of the conductors. The capacitance and inductance per unit length can be expressed as shown in equation (6) and (7), respectively.

$$C = \epsilon_o \epsilon_r \frac{a}{d} \text{ [F/m]} \quad (6)$$

$$L = \mu_o \mu_r \frac{d}{a} \text{ [H/m]} \quad (7)$$

In addition, the resistance R and conductance G are expressed by (8) and (9) respectively.

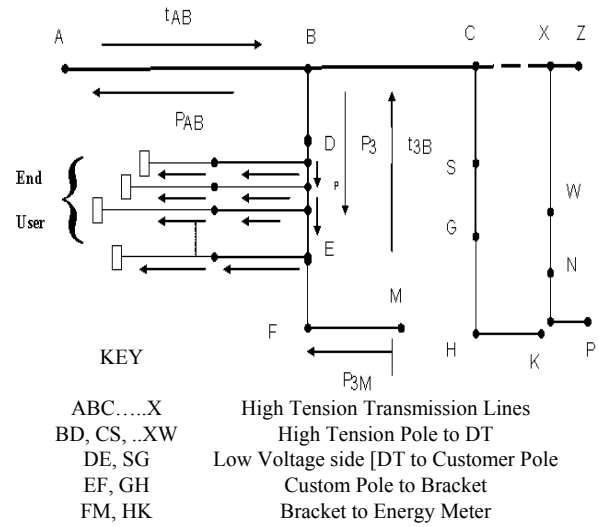


Fig. 4. Signal flow diagram for multi-path propagation from primary substation to secondary substation (distribution transformer).

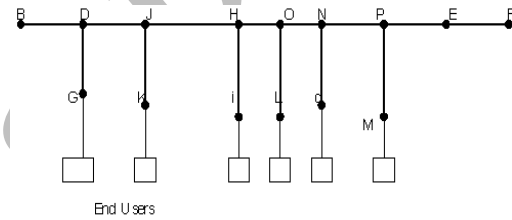


Fig. 5. Analysis of paths in low voltage.

$$R = 2 \left(\frac{R_s}{2\pi a} \right) = \frac{1}{\pi a} \sqrt{\frac{\pi f \mu_{Al}}{\sigma_{Al}}} \text{ [}\Omega\text{]} \quad (8)$$

$$G = 2\pi f C \tan \delta \quad (9)$$

The propagation constant and attenuation function in this section can be represented by (4) and (5).

Fig. 2 is the frequency response of powerline channel under different frequencies. It can be observed that the attenuation at a distance of 4km in PLC is -3 dB, 0.8 dB and 0.7 dB at 2 MHz, 140 kHz and 100 kHz, respectively. Fig. 3 is the frequency response for the link from customer meters to distribution transformers. it can be observed that at 1.2km the attenuation is -1 dB, -0.3 dB and -0.25 dB at 2 MHz, 140 kHz and 100 kHz respectively. However the nature of powerline channel have a number of interconnections, which have to be investigated.

III. MULTI-PATH ANALYSIS

A. From Primary Substation to Distribution Transformer

Fig. 4 is representing the signal flow from primary substation to end-users. Assume Z_{BC} , Z_{BD} and Z_{AB} to be the characteristics impedances of powerline network between distribution transformers connection to high tension pole at DT. Let the parameters P_{AB} and t_{AB} be the reflection and transmission factor respectively. The relations with other transmission line parameters are as given in (10) to (12).

$$P_{AB} = \frac{Z_{BC} \parallel Z_{BD} - Z_{AB}}{Z_{BC} \parallel Z_{BD} + Z_{AB}} \quad (10)$$

$$t_{AB} = 1 - |P_{AB}| \quad (11)$$

TABLE I
MULTI-PATH FROM P/S TO DT POLE

Path No.	Way of the signal	Weighting factor g_i	Length of the path d_i
1	ABC ... XZ	t_{AZ}	AZ
2	ABMBC ... XZ	$t_{AZ} P_{3M} t_{3B}$	AZ+2(DB+DE+EF+FM)
3	ABMBKC ... XZ	$t_{AZ} P_{3M}^2 t_{3B}^2$	AZ+4(DB+DE+EF+FM)
.	.	.	.
N	BD ... WZ	$t_{AZ} P_{3M}^{(N-1)} t_{3B}^{(N-1)}$	AZ+2(N-1)×(DB+DE+EF+FM)

The parameter P_{DE} is the reflection factor within low voltage grid due to interconnection; DE is a part of low voltage poles connecting different end users as shown in Fig. 5. P_E is the reflection experienced by communication signal immediately after leaving the pole at customer premises to bracket. P_F is the reflection between bracket cables and meter cable.

The reflection from distribution transformer to end users due to number of interconnection by end users is represented by equation (13), whereby Z_{DG} is the characteristics impedance of PLC between customer pole and bracket.

$$P_J = \frac{Z_{JK} \parallel Z_{JH} - Z_{DJ}}{Z_{JK} \parallel Z_{JH} + Z_{DJ}} \quad (12)$$

Assuming that the main cable $D \rightarrow F$ have the uniform characteristics impedance, then the corresponding reflections at each point of interconnection and characteristics impedances is as in (13) to (20).

$$P_J = P_H = P_J = P_N = \dots = P_P \quad (13)$$

$$Z_{DJ} = Z_{JH} = Z_{HO} = \dots = Z_{NP} \quad (14)$$

$$Z_{DG} = Z_{JK} = Z_{HJ} = \dots = Z_{PM} \quad (15)$$

For the section DE assuming $N_{\max}$ end users connected per phase, the reflection factor with low voltage can be represented.

$$P_{DE} = 1 - |P_J|^{N_{\max}} \quad (16)$$

$$P_{EF} = \frac{Z_{PE} - Z_{EF}}{Z_{PE} + Z_{EF}} \quad (17)$$

$$P_F = \frac{Z_{MF} - Z_{FE}}{Z_{MF} + Z_{FE}} \quad (18)$$

$$P_3 = P_{DE} P_E P_F \quad (19)$$

$$t_{3B} = 1 - |P_3| \quad (20)$$

For multi-branches with N branches (distribution transformers) the forward reflection and transmission factors are shown in (21) and (22), respectively. However, the cabling per distribution transformer is the same. Assuming that the signal experiences similar reflection resistances.

$$P_{AZ} = P_{AB} P_{BC} \dots P_{XZ} \quad (21)$$

$$P_{AZ} = |P_{AB}|^N \quad (22)$$

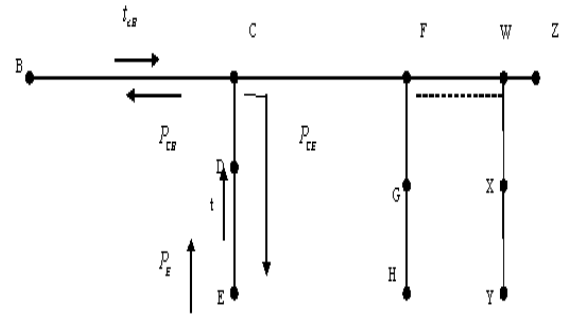


Fig. 6. Block diagram showing multi-path from distribution transformer to customer section of network.

$$t_{AZ} = 1 - |P_{AZ}| \quad (23)$$

Table I presents the characteristics of multi-path power line as a communication network from primary substation to distribution transformer pole.

B. Secondary Substation to Customer Pole

The part BZ is a branch from distribution transformer to nearest branches from secondary substation to customer pole is shown in Fig. 6. Part CD represents customer pole to bracket and part DE represents bracket to data switch (at customer meter) at household. The reflections and transmission factors are given by (24) to (31).

$$P_{CB} = \frac{Z_{CF} \parallel Z_{CD} - Z_{BC}}{Z_{CF} \parallel Z_{CD} + Z_{BC}} \quad (24)$$

$$t_{CB} = 1 - |P_{CB}| \quad (25)$$

$$P_C = \frac{Z_{BC} \parallel Z_{CF} - Z_{CD}}{Z_{BC} \parallel Z_{CF} + Z_{CD}} \quad (26)$$

$$P_D = \frac{Z_{CD} - Z_{DE}}{Z_{CD} + Z_{DE}} \quad (27)$$

$$P_{CE} = P_C P_D \quad (28)$$

$$t_{CE} = 1 - |P_{CE}| \quad (29)$$

$$P_E = \frac{Z_E - Z_{ED}}{Z_E + Z_{ED}} \quad (30)$$

The link $BC=CF=\dots=WZ$, and $CD=FG=\dots=WX$ and $DE=GH=\dots=XY$. The part with the similar cabling will have the same characteristics impedance. Hence Z_E is the characteristic impedance due to load connected and it is assumed to be matched with transmission line.

$$P_{BZ} = P_{CB} P_{FC} P_{WF} \dots P_{WZ} \quad (31)$$

Since the characteristics impedances is the same, then the forward reflection and transmission factors are given by (32) and (33), respectively.

$$P_{CZ} = (P_{CB})^N \quad (32)$$

$$t_{CZ} = 1 - |P_{CZ}| \quad (33)$$

Equations (35) to (39) show their equivalent characteristics impedance where LPDT, BLP and mb subscripts represent low voltage pole to DT, bracket to low voltage pole and meter to bracket cables, respectively.

TABLE II
MULTI-PATH TABLE DT TO END USERS

Path No.	Way of the signal	Weighting factor g_i	Length of the path d_i
1	BCF....WZ	t_{CZ}	BZ
2	BCDEDCF....WZ	$t_{CZ}P_E t_{CE}$	BZ+2(CD+DE)
3	BCDEDCFGHG F..WZ	$t_{CZ}P_E^2 t_{CE}^2$	BZ+4(CD+DE)
.	.	.	.
N	BD.....WZ	$t_{CZ}P_E^{(N-1)} t_{CE}^{(N-1)}$	BZ+2(N-1)×(CD+DE)

$$Z_{BC} = \sqrt{\frac{R_{LPDT} + j\omega L_{LPDT}}{j\omega C_{LPDT}}} \quad (34)$$

$$Z_{CD} = \sqrt{\frac{R_{BLP} + j\omega L_{BLP}}{j\omega C_{BLP}}} \quad (35)$$

$$Z_{DE} = \sqrt{\frac{R_{mb} + j\omega L_{mb}}{j\omega C_{mb}}} \quad (36)$$

$$Z_{BC} = Z_{CF} = Z_{FW} = \dots = Z_{WF} \quad (37)$$

$$Z_{CD} = Z_{FG} = \dots = Z_{WX} \quad (38)$$

$$Z_{DE} = Z_{GH} = \dots = Z_{XY} \quad (39)$$

Table II gives the characteristics of multi-path power line as a communication network from low voltage pole to distribution transformer.

IV. PROPAGATION DELAY

The interconnection node and different path length causes propagation delay or delay term in power line used as a communication network. This behavior in PLC can be modeled by

$$P(\tau) = e^{-j2\pi f\tau_i} \quad (40)$$

The delay τ_i of a path can be calculated from the length d_i and the phase velocity v_p as shown in (41)

$$\tau_i = \frac{d_i}{v_p} \quad (41)$$

With the speed of light in vacuum c_0 and the dielectrics constant ϵ_r of the insulating material, the relation between delays τ_i , length of a path d_i and phase velocity v_p is given by

$$\tau_i = \frac{d_i \sqrt{\epsilon_r}}{c_0} = \frac{d_i}{v_p} \quad (42)$$

V. CHANNEL MODELING ANALYSIS

It can be concluded from the previous sections that power line model from primary substation to customer pole (pole at end users) consist of three parameters; cabling attenuation that changes with frequency and distance, multi-path propagation due to branches and propagation delay. The transfer function of power line channel from primary substation to end users pole is as shown in (43), where g , A and P are weighting factor, cable attenuation and propagation delay in the cable respectively (see

previous sections).

$$H(f, d, N) = \sum_{i=1}^N |g_i(f)| A(f, d) P(\tau) \quad (43)$$

The number of branched network (connected end users) and distribution transformers is equally distributed along the transmission line (power line cable). For 70 end users connected at maximum distance of 1.2 km per feeder the relationship of distance and number of interconnections is given by

$$N_{\max} = \frac{70d_r}{1200} \quad (44)$$

where d_r and $N_{\max}$ are the distance from end users to distribution transformers and end-users (interconnections) per feeder, respectively.

For the channel from distribution transformer to primary substation the relationship is

$$N = \frac{7d}{4000} \quad (45)$$

where N and d are distribution transformers connected to high tension channel and distances from high tension pole to primary substation, respectively. For the case from distribution customer pole to data switch or energy meter and high-tension pole to distribution transformers the frequency response depends only on the cabling used. Hence, the transfer function in this part is given by (46), where γ and l are propagation constant and cable length, respectively.

$$H(f) = \exp(-\gamma l) \quad (46)$$

It is important to relate the transfer characteristics of a powerline channel with other factors that contribute towards attenuation in the channel. These factors are summarized as:

- *Distance*: distance from end users to distribution transformers and distribution transformers to primary substation.
- *Frequency*: the frequency of data transmission f in Hz.
- *Number* of end users and distribution transformers connected.

VI. SIMULATION RESULTS

The interest is mainly in two things; the variation of frequency response with distance, frequency and interconnection (N) that increases at different stages from end users to primary substation. The other is the phase change at different stages. The first factor determines the hoping distance of data transmission, while the second factor determines the need for an equalizer in powerline channel environment.

Figs. 7 and 8 show attenuation as the distances and number of branches increase, respectively from distribution transformer towards the customer household. It can be observed that the attenuation behave linearly as the distance and number of interconnections increases. In addition, due to this attenuation from end users to distribution transformers with 23 interconnections data can be transmitted up to 400 meters. The attenuation at this point is -90 dB, which is very high attenuation.

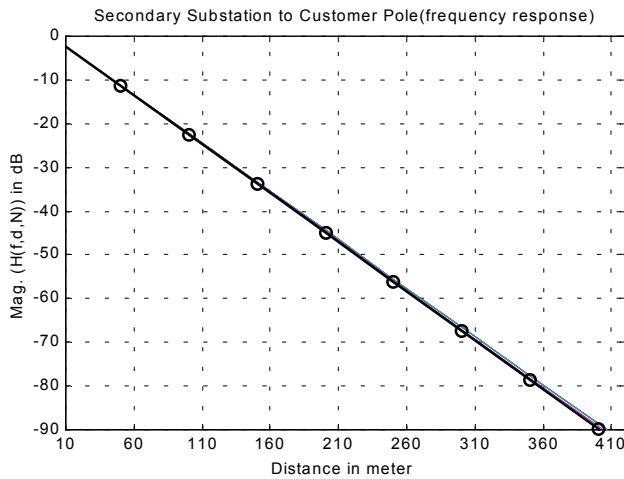


Fig. 7. Frequency response in PLC as distance increases at 100 kHz.

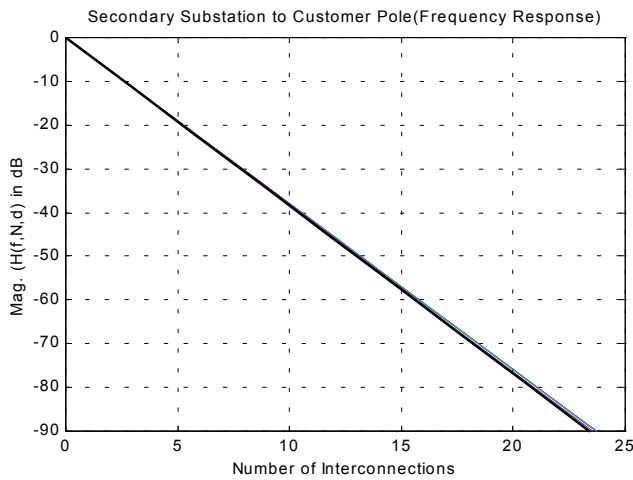


Fig. 8. Frequency response in PLC as the number of branches increases at 100 kHz.

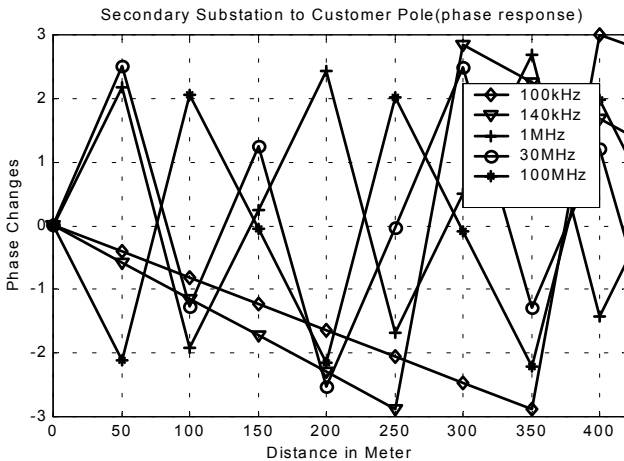


Fig. 9. Phase response in PLC as distance increases along PLC at 100 kHz.

Fig. 9 shows a phase responses dependence on distance. It can be observed that at 100 kHz, data can be transmitted up to 350meters without signal distortions, while for 140 kHz is up to 250meters. In addition for higher frequencies of 1 MHz, 30 MHz and 100 MHz only 50 meters can be covered.

The key observations in this section from primary substations to secondary substation are the same as that observed for distribution transformer to customer pole at households. This indicates that although the size of the

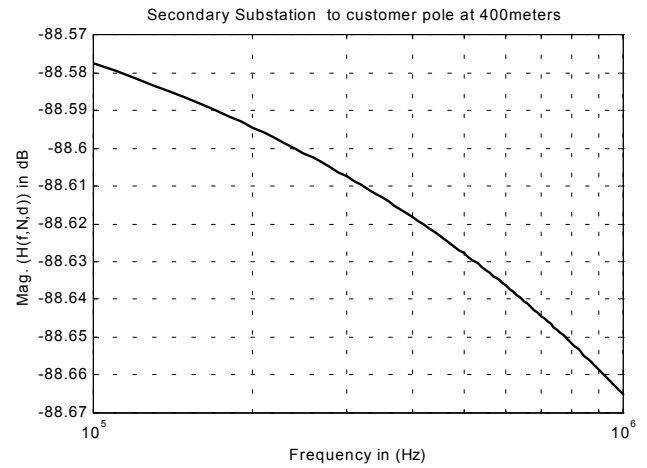


Fig. 10. Frequency response in PLC at 400 meters from DT to customer pole.

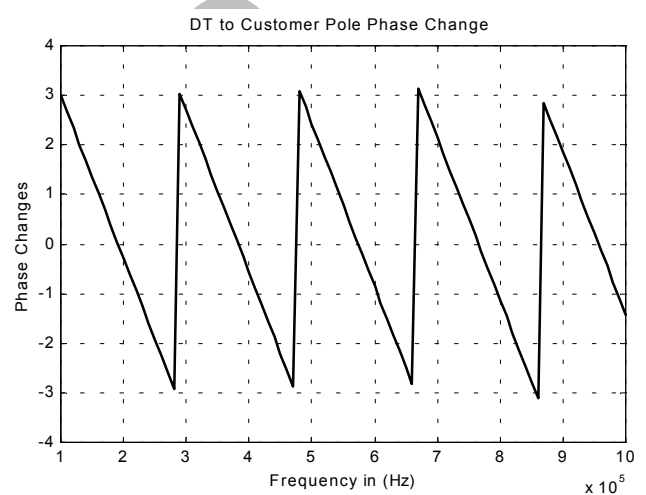


Fig. 11. Phase response at different frequencies from DT to customer pole.

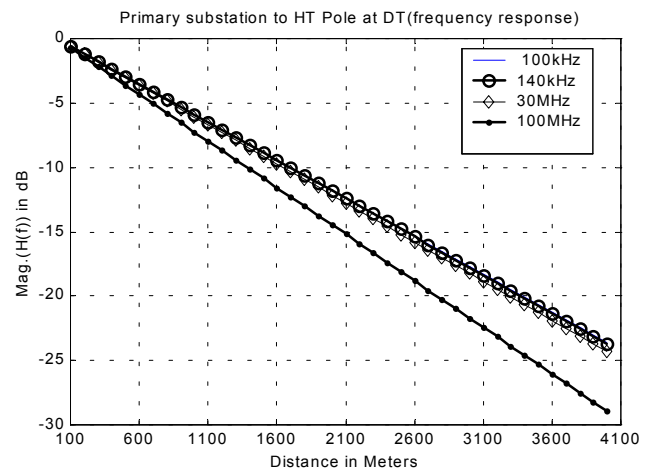


Fig. 12. Frequency response in PLC as distance increases at 100 kHz from P/S to DT pole at DT.

cables used and materials are the same, the behavior in powerline channel is unique. However, the attenuation factors are different due to the actual size of material, size of material, distance and number of interconnections.

Fig. 10 shows the frequency responses in powerline channel. It can be observed that at 400 meters and frequency of 100 kHz the attenuation is -88.58 dB, while at 1 MHz the attenuation is -88.67 dB which indicate that the attenuation in PLC do not depend much on frequency, but

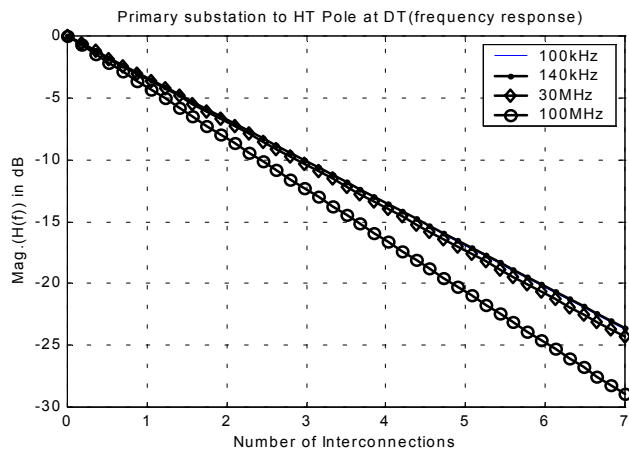


Fig. 13. Frequency response in PLC as number of branches increases at 100 kHz from P/S to DT pole at DT.

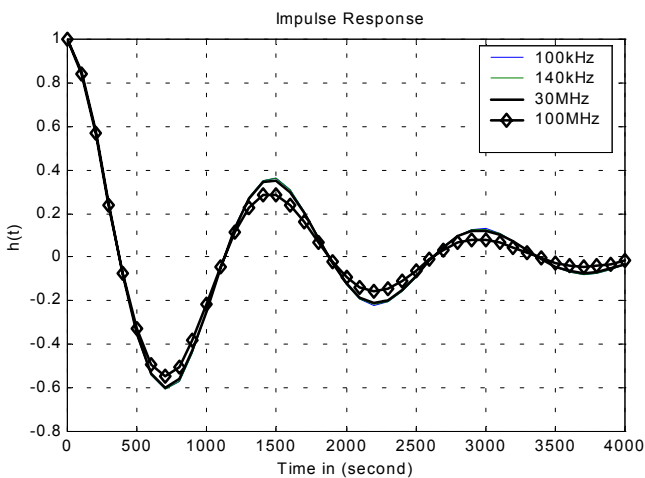


Fig. 14. Time response as distance increases from high tension to HT pole at distribution transformer.

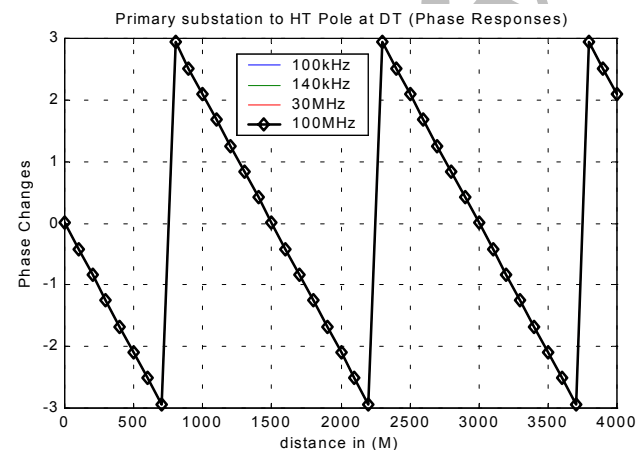


Fig. 15. Phase response in PLC as distances increases at 100 kHz from P/S to DT pole at DT.

more on distances and number of interconnections as observed in Figs. 7 and 8, respectively. Fig. 11 shows the behavior of the phase at the same distance under different frequencies. It can be observed that the phase depends much on frequencies of data transmission. In addition, the bandwidth in powerline channel is very large. Figs. 12 and 13 show that, attenuation increases as distances and the number of branches increases respectively from primary substation to the towards distribution transformers.

Fig. 14 shows the time response in high-tension grid. It can be observed that the signal attenuate with distances in

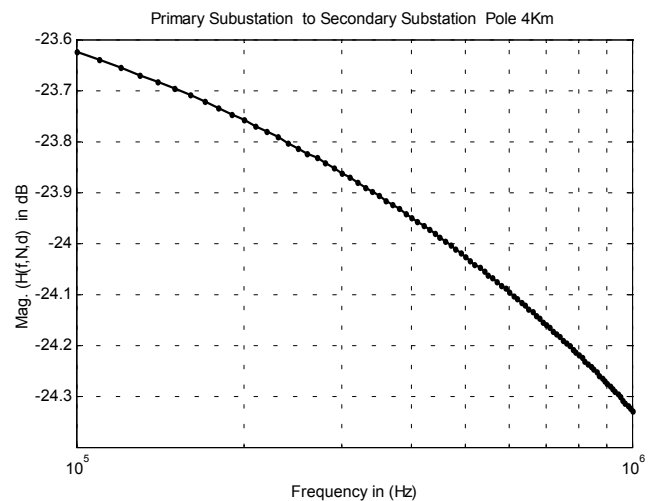


Fig. 16. Frequency response in PLC at 4 Km from P/S to HT pole at DT.

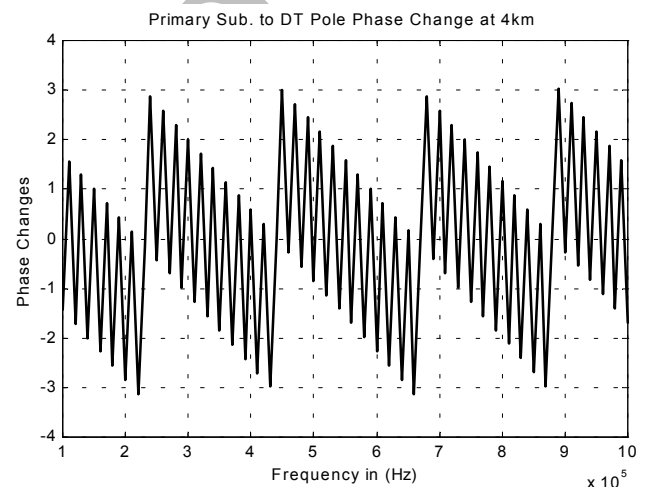


Fig. 17. Phase responses from primary substation to DT pole at 4 Km.

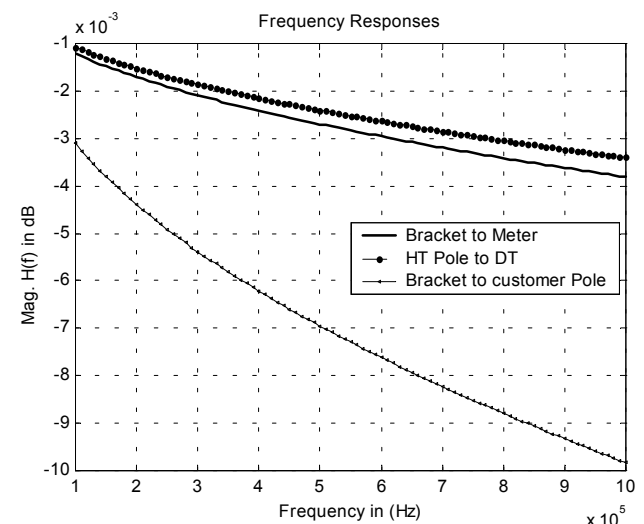


Fig. 18. Frequency responses of different interconnection cables.

such a way that at a distance of 2 km the signal is about 0.2 of the original signal at 300 MHz and less at higher frequencies. This behavior indicates that data transmission in PLC environment needs signal to be amplified or transmitted at higher powers.

Fig. 15 shows the phase responses between primary substation and distribution transformers pole at HT side. Fig. 16 depicts the frequency response in PLC from P/S to high-tension pole at distribution transformer (DT), it can be

observed that the attenuation in this stage is a normal attenuation which do not need any amplification. Fig. 17 is the phase response in PLC from DT to P/S.

Fig. 18 shows the dependence of attenuation on frequencies for different sections from data switch (energy meter) to bracket, bracket to customer pole and distribution transformers to HT pole. It can be realized that the dependence of attenuations to frequency in this part is very small compared to that of other parts. Hence, it can be neglected in most cases.

Fig. 19 depicts the phase response of different interconnection cable where linearity can be observed which indicates that there is no effect on phase of the cable.

VII. CONCLUSION

The modeling schemes for PLC have been presented and discussed. It is clear that the PLC is affected by length of the cable, number of branches determined by the number of customers connected, and propagation delay factors due to nodes from one cable to another.

It has been observed that the data can be transmitted up to 400 m and 4 km in low voltage grid and high tension grid, respectively. The signals to noise ration obtained -88.58 dB and -30 B in low voltage and high voltage, respectively. This indicates that data transmission in low-tension grid transmission needs high power, also different techniques are to be applied to be able to communicate through this channel. In high tension grid the data can be transmitted without need of complicated systems. In addition, to be able to communicate up to distribution transformer in low voltage side at least two regenerative repeaters are necessary.

ACKNOWLEDGEMENT

The first author would like to acknowledge the sponsorship of SIDA/SAREC through the Faculty of Electrical and Computer systems of University of Dar es Salaam.

REFERENCES

- [1] M. Zimmermann and K. Dostert, "A multi-path signal propagation model for the powerline channel in the high frequency range," in *Proc. of the 3rd Int. Symp. on PLC*, Lancaster UK, 1999.
- [2] D. C. Green, *Transmission Principles for Technicians*, Malaysia, 1993, pp. 45-66.
- [3] W. Kwan *et al*, *Design Document for PLLCS: A Power Line Carrier Communications System*, CE Senior Design II document submitted at the Department of Electrical and Computer Engineering Mississippi State University, Dec. 2000
- [4] P. J. Langfeld, "The capacity of typical powerline reference channels and strategies for system design", in *Proc. of the 5th Int. Symp. on Power-Line Communications and Its Applications, ISPLC-2001*, pp. 271-278, Malmo, Sweden, Apr. 4-6, 2001.
- [5] P. Langfeld *et al*, "Powerline communication system design strategies for local loop access," in *Proc. of the Workshop Kommunikationstechnik, Technical Report ITU-TR-1999/2*, pp. 21-26, Jul. 1999.
- [6] H. L. Lutz and J. B. Huber, "Bandwidth efficient Power line Communications based on OFDM," *International Journal of Electronics and Communications Archive für Elektronik und Übertragungstechnik*, vol. 54, no. 1, pp. 2-12, Feb. 2000.

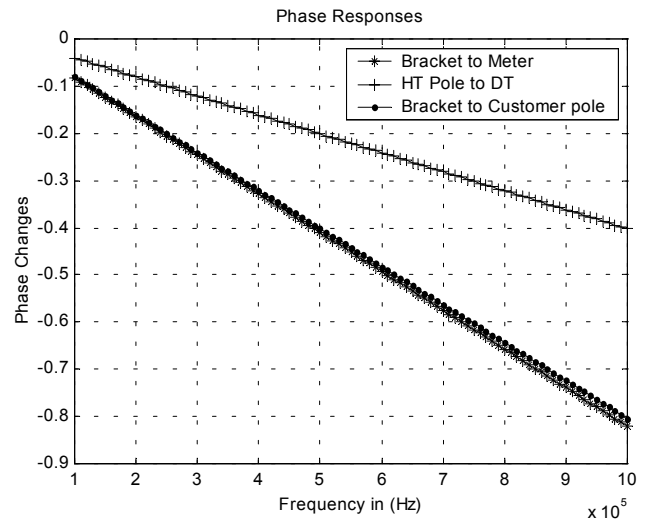


Fig. 19. Phase responses of different interconnection cables.

- [7] A. Matov "A planning tool for high bit rate transmission over power line communication channel," in *Proc. Int. Sym. of Powerline Communication*, pp. 15-20, Malmo, Sweden, Apr. 2001.
- [8] D. S. William, *Elements of Power Systems Analysis*, McGraw-Hill International Editions, fourth Editions, 1988.
- [9] J. Anatory, N. H. Mvungi, and M. M. Kissaka "Powerline network: the solution of communication to non-urban area and links to cellular, PSTN and PSDN" in *Proc. Eastern Africa Power, Telecommunication and Mining Industry Conversion (EAPIC, EATIC, EAMIC)*, pp. 196-225, Loyal Palm, Dar Es salaam, Sep. 2002.

J. Anatory is holding B.Sc. and M.Sc. degrees in Electrical Engineering of University of Dar es Salaam, Tanzania, which he received in 1998 and 2003, respectively. From 1998 he was with Beta Communication Consulting Co. (T) Limited as a Software and IT Engineer before joining again the University of Dar es salaam in 2001 as a Master Student. Currently, Mr. J. Anatory is an Assistance Lecturer in the Department of Computer and Systems Engineering of University of Dar es Salaam. His research interest includes power-line communication, rural telecommunications accessibility, communication networks, control engineering and metering technologies.

N. H. Mvungi graduated with a B.Sc. in Electrical Engineering at the University of Dar es Salaam in 1978. Since then he has studied in Salford University (M.Sc.) and Leeds University (PhD). He worked with Phillips Center for Technology in Eindhoven for one year. Since his graduation in 1978, he has been working at the University as an academician. He is currently a Senior Lecturer. His interest is in control and instrumentation, computer communication and applied electronics. His research interests include lightning protection, rural access, power quality aspects, and remote monitoring and control of energy consumption. Dr. Mvungi is the Head of the Computer and Systems Engineering Department of the University of Dar es Salaam.

M. M. Kissaka received B.Sc. in Electrical engineering from the University Dare S Salaam, Tanzania, in 1989 and the Ph.D. degree in telecommunications engineering from the University of Manchester, United Kingdom, in 1994. Since 1989 he has been with the University of Dar es Salaam where he is currently a Lecturer in the Department of Telecommunications Engineering, Faculty of Electrical and Computer Systems Engineering. His research interest includes rural telecommunications and computer networks. Dr. Kissaka is a registered professional engineer with engineers registration board (ERB) of Tanzania.