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Comparison of different Channel Modeling Techniques used in the BPLC Systems

Justinian Anatory and Nelson Theethayi

***Abstract*—**The paper compares different channel models used for modeling Broadband Power-Line Communication (BPLC) system. The models compared are Zimmermann and Dostert, Philipps, Anatory *et al* and Anatory *et al* generalized Transmission Line (TL) model. The validity of each model was compared in time domain with ATP-EMTP software which uses transmission line approach. It is found that for a power-line network with minimum number of branches all the models give similar signal/pulse time responses compared with ATP-EMTP software; however, Zimmermann and Dostert model indicates the same amplitude but different time delay. It is observed that when the numbers of branches are increased only generalized TL theory approach results are comparable with ATP-EMTP results. Also the Multi-Carrier Spread Spectrum (MC-SS) system was applied to check the implication of such behavior on the modulation schemes. It is observed that using Philipps on the underground cable can predict the performance up to 25dB better than other channel models which can misread the actual performance of the system. Also modified Zimmermann and Dostert under multipath can predict a better performance of about 5dB better than the actual predicted by Generalized TL theory. It is therefore suggested for a realistic BPLC system design and analyses the model based on generalized TL theory be used.

***Keywords*—**Broadband Power line Channel Models, load impedance, Branched network.

I. Introduction

FOR an efficient communication using the power line networks the channel's performance has to be evaluated to a greater accuracy. For this an appropriate and more accurate model is needed which can be used as a tool in the design of suitable communication equipments of PLC systems [1]. Researchers, in the recent past have attempted to come up with appropriate channel models, some of them being somewhat channel dependant, e.g. the indoor applications models by Banwell and Galli [2] and the low and medium voltage applications models by Zimmermann and Dostert [3], Hensen and Schulz [4], Philipps [5], etc. Some of the low and medium voltage channel models were extended to the indoor applications too. Some indoor models have been derived from measurements, e.g., Canete [6], [7]. Generally, the modeling adopted can be categorized as either time-domain models or frequency domain models [8]. It is however to be noted that the channels performance can be more accurately assessed from channel transfer functions i.e., through frequency domain models. Another channel model based on transmission and reflection factors in conjunction with the propagation constants was proposed by Anatory *et al.* [9] for a PLC network with two conductor transmission line (TL) systems (one phase conductor and one return conductor).

The recent model by Anatory *et al.*, is based on the generalized TL theory approach [1] for determining the channel responses. It uses all the known principles of TL theory and the model is derived based on the modal analyses. Although, in the literature various types of channel models exist we feel that a comparative and sensitivity analyses is needed for more accurate channel performance studies within PLC. This paper compares Zimmermann and Dostert [3], Philipps [5], Anatory *et al.* [9] and Anatory *et al.* generalized TL approach [1]. The paper has considers cases whereby a power line channel with adjacent conductor return for different cases of distributed branches within the link between transmitting and receiving ends. The results in time domain are compared using widely used ATP-EMTP software by power engineers [10] which also uses transmission line approach.

II. Power-Line Channel Models

The transfer function of power line channel model proposed by Philipps [5] is given by (1). In (1) N is the number of possible signals flow paths, each path delayed by time τ_i is multiplied by a complex factor ρ_i. The parameter ρ_i is the product of transmission and reflection factors. In (1) the parameters f, c_o, d_i and ε_r are frequency, velocity of light, path length and relative permittivity respectively.

$$H(f) = \sum_{i=1}^{N} \rho_i e^{-j2\pi f \tau_i} \tag{1a}$$

$$\rho_i = |\rho_i| \cdot e^{j\phi_i}, \; \phi_i = \arctan\left(\frac{\mathrm{Im}(\rho_i)}{\mathrm{Re}(\rho_i)}\right) \tag{1b}$$

$$t_i = \frac{d_i}{v_p} \tag{1c}$$

$$v_p = \frac{c_o}{\sqrt{\varepsilon_r}} \tag{1d}$$

Zimmermann and Dostert [3] developed a channel model to account for the attenuation of the signal flow as given in (2). In (2) each path is characterized by weighting factor g_i which is the product of transmission and reflections factor

J. Anatory is with School of Virtual education, College of Informatics and Virtual Education, University of Dodoma, Tanzania. (Phone: +255262310007; fax: +255262323000; e-mail: anatory@engineer.com).
Nelson Theethayi is with Bombardier Transportation, Sweden.

with path length d_i. The attenuation factor is modeled by the parameters a_0, a_1 and k, which are obtained data from measurements also it employs top down approach. The model was extended to bottom-top model by deriving parameters from actual networks taking into consideration the connected loads [3]. The expressions are as shown in (3), where $t_{d_i} = \frac{d_i}{v_p}$ and $v_p = \frac{c_o}{\sqrt{\varepsilon_r}}$ also $v_p = \frac{1}{\sqrt{L_e \cdot C_e}}$. In 3b the parameters L_e, C_e, R and G are per unit length inductance, capacitance, resistance and conductance of a conductor respectively. Γ_{AD}, Γ_{2C} and ρ_{2D} are transmission factor from point A towards D, transmission factor along line 2 to point C, reflection factor along line 2 to point D respectively.

$$H(f) = \sum_{i=1}^{N} g_i e^{-(a_0 + a_1 f^k).d_i} e^{-j2\pi f \frac{d_i}{v_p}} \quad (2)$$

$$H(f) = \sum_{i=1}^{N} g_i^{''}(f) A^{''}(f_i, d) \cdot \exp(-j2\pi f \tau_{d_i}) \quad (3a)$$

$$A^{''}(f_i, d_i) = \exp(-\sqrt{(R + j\omega L_e)(G + jwC_e)}) \cdot d_i \quad (3b)$$

$$g^{''}_i = \Gamma_{AD} \rho_{2D}^{(i-1)} \Gamma_{2C}^{(i-1)} \quad (3c)$$

Anatory *et al.* [9] developed a generalized case applicable to any line configuration with distributed branches along the line from transmission point to the receiver. The transfer function of such network is given by (4a). In (4a) the parameters M_T is the total number of distributed nodes, d is any referenced node (1… M_T), $H_{mnd}(f)$ is the transfer function between line n to a referenced load m at a referenced node d. For more information about such parameters the reader are advised to use the papers such as [9].

$$H_{mM_T}(f) = \prod_{d=1}^{M_T} \sum_{M=1}^{L} \sum_{n=1}^{N_T} \mathrm{T}_{Lmd} \alpha_{mnd} H_{mnd}(f) \qquad n \neq m \quad (4a)$$

$$\alpha_{mnd} = P_{Lnd}^{M-1} \rho_{nmd}^{M-1} e^{-\gamma_{nd}(2(M-1)\ell_{nd})} \quad (4b)$$

$$P_{Lnd} = \begin{cases} \rho_s & d = n = 1 (source) \\ \rho_{Lnd}, & otherwise \end{cases} \quad (4c)$$

The recent generalized transmission line (TL) theory was developed by Anatory *et al.* [1]. Note that the procedure for the obtaining the transfer function is the same i.e. writing the voltage ad current boundary conditions at all the nodes and solving for the unknown modal currents. The transfer function for the voltage between any load point Z_{nm} and the sending end is given by (5a). In (5a) Z_{Cnm}, Z_{nm}, γ_{nm}, L_{nm} and L_n are characteristic impedance of line segment nm, terminal load impedance of line nm, propagation constant of line segment nm, shortest length of line segment nm, and shortest line length from the sending end to the node n under consideration, respectively. Note that all parameters with nn means the consideration is at the node.

$$H_{nm}(f) = \frac{Z_{C11} + Z_s}{Z_{C11}} Z_{Cnm} \left(e^{-\gamma_{nm} L_{nm}} \beta_{nm} + e^{\gamma_{mn} L_{nm}} \right) A_{nm} \frac{1}{A_1^+ \beta_{11} + A_1^-} \quad (5a)$$

$$\beta_{nn} = \frac{C_{nn}^- - P_n B_{nn}^-}{C_{nn}^+ + P_n B_{nn}^+} \quad (5b)$$

$$\boldsymbol{P_n} = \frac{\boldsymbol{e_{nm(1)}}}{\boldsymbol{a_{nm(1)}}} + \frac{\boldsymbol{e_{nm(2)}}}{\boldsymbol{a_{nm(2)}}} \quad (5c)$$

$$\beta_{nm} = \frac{(1 - Z_{Cnm}/Z_{nm}) e^{-\gamma_{nm} L_{nm}}}{(1 + Z_{Cnm}/Z_{nm}) e^{\gamma_{nm} L_{nm}}} \quad (5d)$$

$$\boldsymbol{A_{nm}} = \frac{\boldsymbol{a_n a_{n-1} \ldots\ldots\ldots a_1}}{\boldsymbol{a_{nm} a_{(n-1)(n)} a_{(n-2)(n-1)} \ldots\ldots\ldots\ldots a_{12}}} \quad (5e)$$

$$a_{nm} = B_{mn}^+ \beta_n + B_{mn}^- \quad (5f)$$

$$e_{nm} = C_{mn}^- - C_{mn}^+ \beta_n \quad (5g)$$

$$\beta_n = \begin{cases} \beta_{(n+1)(n+1)} & to \quad node \quad n+1 \\ \beta_{nm} & to \quad load \quad m \end{cases} \quad (5h)$$

$$a_{mn} = B_{nm}^+ \beta_{nm} + B_{nm}^- \quad (5i)$$

$$a_n = B_{nn}^+ \beta_{nn} + B_{nn}^- \quad (5j)$$

$$B_{mn}^+ = Z_{Cmn} e^{-\gamma_{mn} L_n} \quad (5k)$$

$$B_{mn}^- = Z_{Cmn} e^{\gamma_{mn} L_n} \quad (5l)$$

$$B_{nm}^+ = Z_{Cnm} e^{-\gamma_{nm} L_n} \quad (5m)$$

$$B_{nm}^- = Z_{Cnm} e^{\gamma_{nm} L_n} \quad (5n)$$

$$C_{mn}^+ = e^{-\gamma_{mn} L_n} \quad (5o)$$

$$C_{mn}^- = e^{\gamma_{mn} L_n} \quad (5p)$$

$$B_{nn}^+ = Z_{Cnn} e^{-\gamma_{nn} L_n} \quad (5q)$$

$$B_{nn}^- = Z_{Cnn} e^{\gamma_{nn} L_n} \quad (5r)$$

$$C_{nn}^+ = e^{-\gamma_{nn} L_n} \quad (5s)$$

$$C_{nn}^- = e^{\gamma_{nn} L_n} \quad (5t)$$

In equation (5a), $A_1^+ = Z_{C11} + Z_S$, and $A_1^- = Z_{C11} - Z_S$.

For all models the received signals V_R can be obtained using (6), where by Z_L, H(f) and Zs are the load impedance at the receiving terminal, transfer function and load impedance of the transmitter respectively.

$$V_R(f) = H(f) * \left(\frac{Z_L}{Z_L + Z_s} \right) V_s \quad (6)$$

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III. Power Line Network with ADJACENT RETURN Conductor- Lossless Cases

A. Power line Network Configuration with one branch

Consider power line network as shown in Fig. 1, Z_S, Vs, Z_{L1} and Z_{L2} are source impedance, source voltage, load impedance at node C and load impedance at load D, respectively. The length of line segment AB, BD and BC was considered as 60m, 200m and 100m respectively. Per unit length inductances and capacitances was taken as 0.44388µH/m and 0.61734pF/m respectively for all the line segments. A 2V rectangular pulse with width of 1µs shifted by 0.5µs was considered as the voltage source injection and was applied to the Phillips [3], Zimmermann and Dostert [5], Anatory *et al.* [9] and Anatory *et al.* generalizes TL theory [1] models. In the cases of Phillips, Zimmermann and Dostert models 10 paths was considered. In Anatory *et al.* [9] model 10 total numbers of reflections were considered. In the simulations Z_{L1} was kept open while Z_S and Z_{L2} were terminated in the characteristic impedance. The voltage was calculated across Z_{L2}.

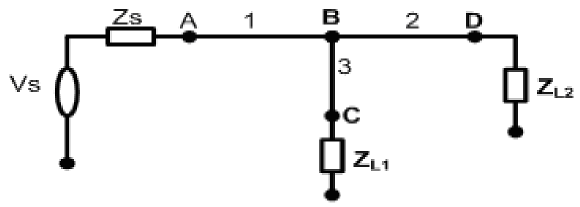

Fig. 1 Power line Network Configuration with one branch

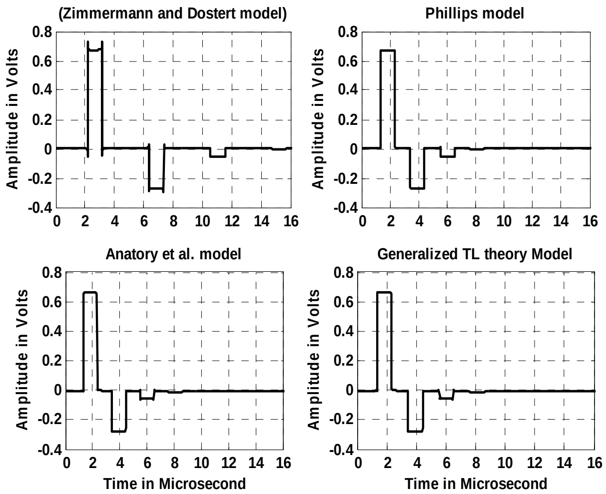

Fig. 2a Comparisons for power line channel models for a power line network with one branch.

Fig. 2a shows the simulation results for Phillips, Zimmermann and Dostert, Anatory *et al.* and the Anatory *et al.* generalized TL theory models. It is observed all the models above have similar results while Zimmermann and Dostert [5] model shows deviation along the time axis, i.e., the instances of voltage peaks or dips (time delays of signals) are not consistent with other models. The validity of the models for this configuration was implemented in ATP-EMTP software and the corresponding results are shown in Fig. 2b, which confirms that Phillips, Anatory *et al* and generalized TL theory models are consistent. Then let us consider a case of power line configuration with two distributed branches in the link between transmitting and receiving ends.

B. Power line Network Configuration with two Distributed branches

Consider power line network as shown in Fig. 3, wherein Z_S, Vs, Z_{L1}, Z_{L2} and Z_{L3} are source impedance, source voltage, load impedance at node E, load impedance at node D and load impedance at load F respectively. The length of line segment AB, BC, BE, CD and CF are 200m. Per unit length inductances and capacitances of all line segments are the same as in previous case. The same rectangular pulse as in previous case was used as voltage source in the Phillips [3], Zimmermann and Dostert [5], Anatory *et al.* [9] and Anatory *et al.* generalized TL theory model [20]. In the cases of Phillips, Zimmermann and Dostert models 10 paths were considered. In Anatory *et al* [9] model 10 total numbers of reflections were considered. In the investigation, Z_{L1} and Z_{L2} were kept at 20 Ω and 50 kΩ, respectively; while Z_S and Z_{L3} were terminated in 85 Ω. Fig. 4a shows the simulations results for all cases. It is clearly observed that the Phillips and Anatory *et al.* models have similar results while Anatory *et al.* generalized TL theory model predicts different responses after about 10 µs.

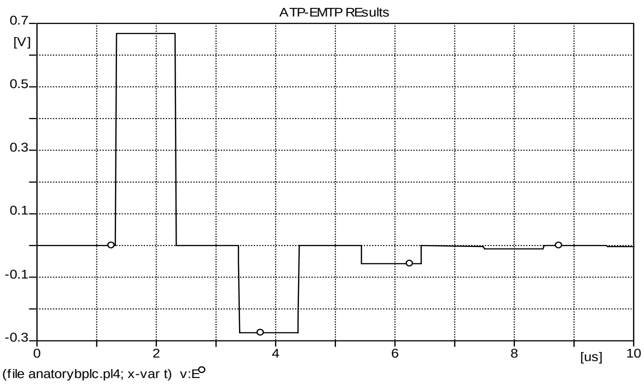

Fig. 2b Simulations using ATP-EMTP software for a power line network with one branch

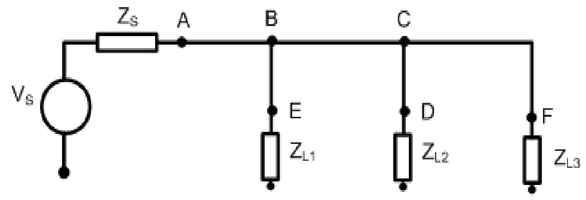

Fig. 3 Network Configuration with distributed branches

Zimmermann and Dostert model indicates similar amplitude but with different time delays as observed in the previous case. The configuration was implemented in ATP-EMTP software, and the corresponding simulations are shown in Fig. 4b. It is evident that the generalized TL theory model predictions are consistent with the ATP-EMTP result (compare the amplitudes of all models even after 10 µs), which indicates that the generalized TL theory model is more accurate, compared to other models. From the above observations, it is found that the Zimmermann and Dostert model might be incapable of predicting the delay spread aspects in BPLC based on TL theory.

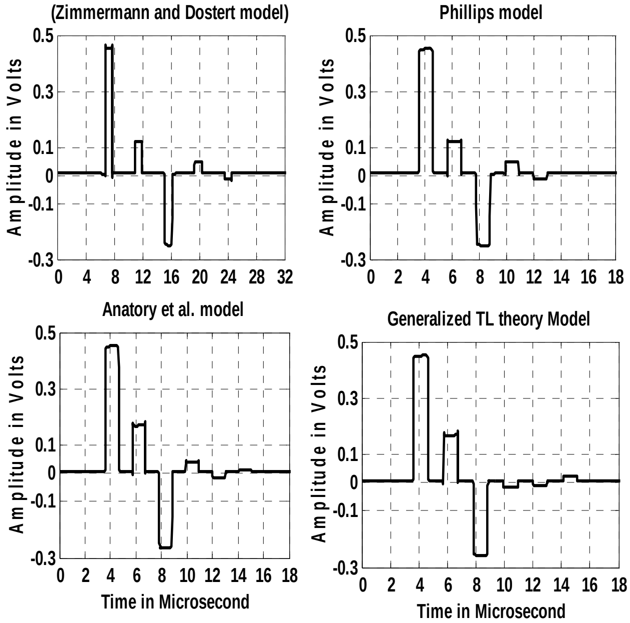

Fig 4a Comparisons for power line channel models for a power line network with two distributed branches

IV. Power Line Network with ADJACENT RETURN Conductor- Loss Cases

Consider power line network cables with configuration as shown in fig. 3, wherein Z_S, Vs, Z_{L1}, Z_{L2} and Z_{L3} are source impedance, source voltage, load impedance at node E, load impedance at node D and load impedance at load F respectively. The length of line segment AB, BC, BE, CD and CF are 200m. Per unit length inductances and capacitances of all line segments are taken as 0.44388μH/m and 0.61734pF/m respectively. The conductance and resistance expression was considered as (7) and (8) respectively. In (7) and (8) the parameters δ , σ , μ and r are the depth factor, conductivity of the conductor, permeability of the conductor and radius of the conductor respectively. In this case the conductivity and conductance was considered as 5.8e7 and 4e-7 respectively. the radius of the conductor connecting the sending and receiving ends were considered as 0.69099mm, while for branched cables was considered as 0.39894mm. In the investigation Z_{L1} and Z_{L2} were kept at 10MΩ respectively, while Z_S and Z_{L3} were terminated in 85Ω. A 2V rectangular pulse with width of 1μs shifted by 0.5μs voltage source was injected in the Phillips [3], Zimmermann and Dostert [3], Anatory *et al* [9] and generalize TL theory model [1]. In the cases of Phillips, Zimmermann and Dostert models 10 paths were considered. In Anatory *et al* [9] model 10 total numbers of reflections were considered. Fig. 5 shows the simulations results for all cases. It is observed that Phillips model is not affected by loss cases of a power line channel. Other models are affected by loss cases. This concludes that in Phillips models apart from giving incorrect amplitudes at the late time the model is not also appropriate for lossy cases which is real case in power line network infrastructure.

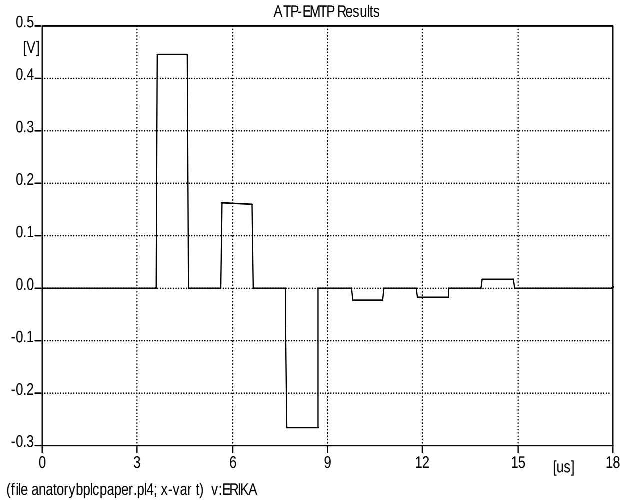

Fig. 4b Simulations using ATP-EMTP software for a power line network with two distributed branches

$$G = 2\pi f C \tan\delta \qquad (7a)$$

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \qquad (7b)$$

$$R = \frac{1}{\pi \sigma r^2} + \sqrt{2 j \pi f} \cdot \sqrt{\frac{\pi \, \mu/\sigma}{2\pi r}} \qquad (8)$$

V. Improved Zimmermann and Dostert Model For Power Line Network with ADJACENT RETURN Conductor- Loss Cases

In this section we looked at the way Zimmermann and Dostert [3] can be improved. Consider power line network cables with configuration as shown in fig. 3, wherein Z_S, Vs, Z_{L1}, Z_{L2} and Z_{L3} are source impedance, source voltage, load impedance at node E, load impedance at node D and load impedance at load F respectively. The length of line segment AB, BC, BE, CD and CF are 200m. Per unit length inductances and capacitances of all line segments are taken as 0.44388μH/m and 0.61734pF/m respectively. The conductance and resistance expression was considered as (7) and (8) respectively. In (7) and (8) the parameters δ , σ , μ and r are the depth factor, conductivity of the conductor, permeability of the conductor and radius of the conductor respectively. In this case the conductivity and conductance was considered as 5.8e7 and 4e-7 respectively. The radius of the conductor connecting the sending and receiving ends was considered as 0.69099mm, while for branched cables were considered as 0.39894mm. In the investigation Z_{L1} and Z_{L2} were kept at 10MΩ respectively, while Z_S and Z_{L3} were terminated in 85Ω. Zimmermann and Dostert [3] model was implemented as in (7) and (8). Note that in (7) and (8) the path length in the delay parameter has been removed. A 2V rectangular pulse with width of 1µs shifted by 0.5µs voltage source was injected in the Phillips [3], Zimmermann and Dostert [5], Anatory *et al* [9] and generalize TL theory model 1]. In the cases of Phillips, Zimmermann and Dostert models 10 paths were considered. In Anatory *et al* [9] model 10 total numbers of reflections were considered. Fig. 6 shows the simulations results for all cases. It is observed in terms of time delay all models are comparable which indicates that in Zimmermann and Dostert [3] model the delay parameters should be removed.

$$H_{\mathrm{Im}\,proved}(f) = \sum_{i=1}^{N} g_i e^{-(a_0 + a_1 f^k).d_i} e^{-j2\pi f \frac{1}{v_p}} \quad (9)$$

$$H_{\mathrm{Im}\,proved}(f) = \sum_{i=1}^{N} g_i^{''}(f) A^{''}(f_i, d) \cdot \exp(-j2\pi f \frac{1}{v_p}) \quad (10a)$$

$$A^{''}(f_i, d_i) = \exp(-\sqrt{(R + j\omega L_e)(G + jwC_e)}) \cdot d_i \quad (10b)$$

$$g^{''}_i = \Gamma_{AD} \rho_{2D}^{(i-1)} \Gamma_{2C}^{(i-1)} \quad (10c)$$

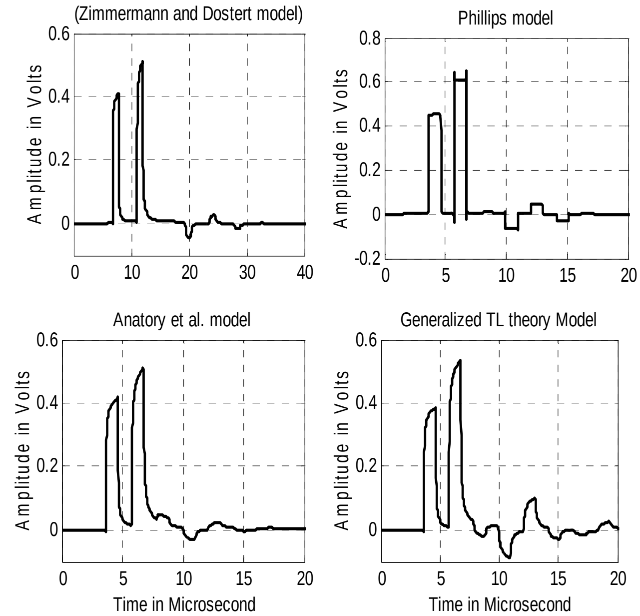

Fig. 5 Comparisons for power line channel models for a power line network with two distributed branches with terminal loads terminated in 10M-ohms [11]

VI. Model Comparisons for Underground Cables Powerline Link

Consider power line network cables with configuration as shown in fig. 7, wherein Z_S, Vs, Z_L are source impedance, source voltage, and load impedance at the receiving end respectively. The number of branches between A and J was eight and distributed equally between sending end and receiving ends. The lengths of branched line are 15m. Per unit length inductances and capacitances of all line segments between A and J are taken as 0.32735µH/m and 0.27191pF/m respectively while the per unit length inductances and capacitances for branched line length are taken as 0.45179µH/m and 0.19702pF/m respectively. The conductance and resistance expression was considered as (7) and (8) respectively. The radius of the conductor connecting the sending and receiving ends was considered as 0.69099mm, while for branched cables were considered as 0.39894mm. In the investigation all terminal loads including Z_S and Z_L were terminated in characteristics impedances.

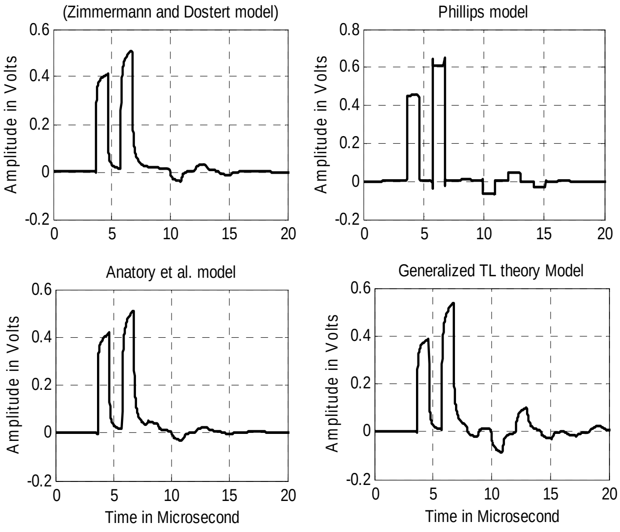

Fig. 6 Comparisons for power line channel models with Zimmermann and Dostert [5] improved for a power line network with two distributed branches with terminal loads terminated in 10M-ohms [11]

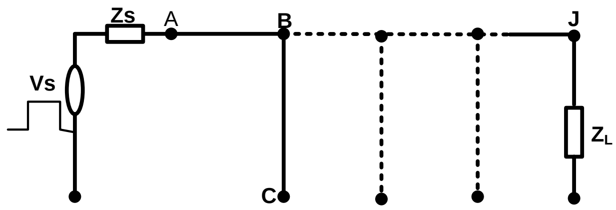

Fig. 7 Network Configuration with distributed branches

A. Frequency responses

Firstly all terminal loads were terminated in the characteristics impedances then in higher impedances. The higher impedances were considered as 1KΩ. Phillips [5], Zimmermann and Dostert [3], Anatory *et al* [9] and generalize TL theory model [1] were applied in the links. In the cases of Phillips, Zimmermann and Dostert models 10 paths were considered. In Anatory *et al* [9] model 10 total numbers of reflections were considered. Figure 8 is the channel frequency responses for underground cables when all terminals are terminated in the characteristics impedances. It can be observed that Phillips model doesn't attenuate with frequencies while the rest of the models attenuate with frequencies. The position of notches and peaks for all models are the same. At higher frequencies, i.e at 20MHz there is difference of 20dB using generalized TL theory model in comparison with modified Zimmermann and Dostert [3] and Anatory *et al* [9]. Figure 9 shows the frequency responses for all models when all branches for a configuration shown in figure 7 are terminated in 1KΩ. It can be observed that except Phillips Model which doesn't attenuate with frequency the rest models attenuate with frequencies. However it has been observed that at higher frequencies generalized TL theory model is attenuating more compared to other models. For example at 25MHz generalized TL theory model, modified Zimmermann and Dostert [3] and Anatory *et al* is at -55dB, -45dB and -50dB respectively.

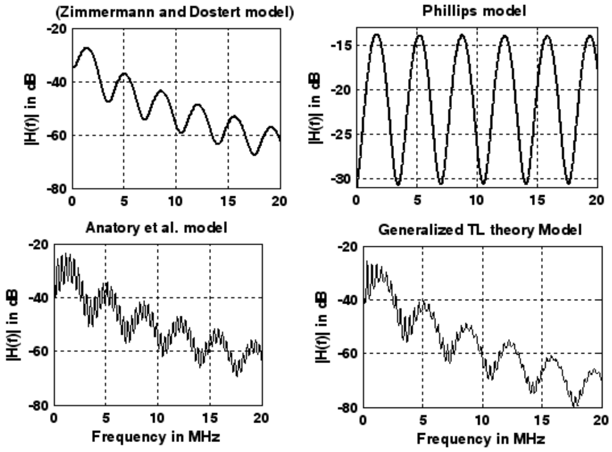

Fig. 8 Frequency Response Comparisons for underground power line channel models with improved Zimmermann and Dostert [3] for a power line network with eight distributed branches with terminal loads terminated in characteristics impedances [11]

VII. Conclusion

In this paper different power line channel models namely, Phillips [3], Zimmermann and Dostert [5], Anatory *et al.* [7] and Anatory *et al.* generalized TL theory model [1,12] are compared. The comparison is done in time domain and ATP-EMTP software is used to check the validity of the model responses. Two important findings are:

1. It is found that Zimmermann and Dostert model predicts incorrect time delays for the responses even though the amplitudes are comparable with other models.
2. As a number of branches increase all the models deviate except the Anatory *et al.* generalized TL theory model [1] is comparable with that of the ATP-EMTP software predictions which is based of transmission line theory.
3. For underground cables Phillips model is inappropriate since it doesn't capture the attenuation factors of the cable which can lead to inappropriate performances using multicarrier systems.
4. In the case of branched power line channel Zimmermann and Dostert model is not suitable since it can predict inappropriate performances.

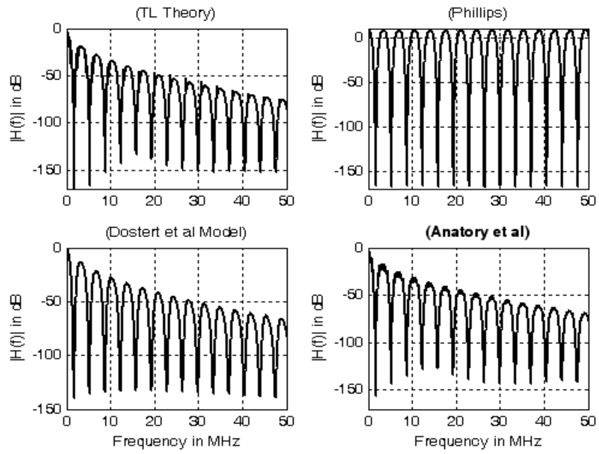

Fig. 9 Frequency Response Comparisons for power line channel models with improved Zimmermann and Dostert [3] for a power line network with eight distributed branches with terminal loads terminated in 1K-ohms [11]

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Justinian Anatory (S'06–M'08) received the B.Sc. and M.Sc. degrees in electrical engineering and the Ph.D. degree in telecommunications engineering from the University of Dar es Salaam, Dar es Salaam, Tanzania, in 1998, 2003, and 2007, respectively. He was a Software and IT Engineer with Beta Communication Consulting Co. (T) Ltd., Dar es Salaam, before rejoining the

University of Dar es Salaam in 2001. He was a Lecturer with the Faculty of Electrical and Computer Systems Engineering, University of Dar es Salaam. He was a Visiting Researcher in the School of Electrical and Information Engineering, University of Witwatersrand, Johannesburg, South Africa, in 2002 and Visiting Researcher at the EMC Group of the Division for Electricity, Uppsala University, Uppsala, Sweden, in 2005 and 2006.

In 2008, he was a Postdoctoral Research Fellow in the Division of Electricity, University of Uppsala, Sweden. Currently, he is a Senior Lecturer and Dean School of Virtual Education, College of Informatics and Virtual Education, University of Dodoma. He has more than 42 publications of which 21 are in the international journals. His research interest includes power-line communication, wireless communication, communication networks, and teletraffic engineering.

Dr. Anatory is a member of the IEEE Power Engineering Society (PES), IEEE Computer Society, IEEE Communications Society, and IEEE Vehicular Technology Society. He is a Registered Engineer with the Engineers Registration Board (ERB) of Tanzania and is a member of Board of Directors of Tanzania Communications regulatory Authority (TCRA).

Nelson Theethayi (S'04-M'06) was born in India, in 1975. He received the B.E. degree in electrical and electronics (Hons.) from the University of Mysore, Mysore, India, in 1996, the M.Sc. (Engineering) degree in high voltage engineering from the Indian Institute of Science, Bangalore, India, in 2001, and the Ph.D. degree in electricity with a specialization in electrical transients and discharges from Uppsala University, Uppsala, Sweden, in 2005. He was employed as a researcher at the EMC group of the Division for Electricity of Uppsala University. Currently, He is working as Electrical System Engineer with Bombardier Transportation, Sweden. His research areas are electromagnetic compatibility, high voltage engineering, electrical power systems, lightning interaction, and lightning protection.

Dr. Theethayi is a member of Subcommittee "Lightning" of the Technical Committee TC5 of the IEEE EMC Society, IEEE Dielectrics and Electrical Insulation Society (DEIS), IEEE Power Engineering Society (PES), and IEEE Industry Applications Society (IAS).