Modeling of Broadband Power Line Communication in last-mile networks

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Abstract— **For last-mile networks the in-building electric power lines are considered an attractive medium for high-speed data transmission. In this paper we consider the channel response in the 1-30MHz band. The development of a Broadband Power-Line Communications (BPLC) network topology is analyzed so as to obtain better performance through channel modeling. The performance of the system by varying the transceiver positions and distance between derivation box to outlets with load and without load scenarios are studied. A model of a floor plan of an apartment building is selected and the characteristics of the channel responses for various topologies are examined with the help of FTW simulator. Thus, the importance in modeling the network topology is investigated.**

***Index Terms*— Power Line Communications (PLC), FTW Simulator, Network Topology, last-mile network, power line channel modeling.**

I. Introduction

Power Line Communication (PLC) is a communication technology that enables sending data over existing power cables. With power cables running to an electronic device one can both power it up and at the same time control or retrieve data from it. One of the main attractions is its vast geographical coverage. Since electrical power lines have reached mostly all rural areas, the BPL (Broadband Power Line) technology can provide broadband services in many underserved areas where other technologies could not reach due to technical and/or economical issues. The pre-installed infrastructure and ample access points are additional advantages. For many years, power lines have been used for narrowband PLC which works at lower frequencies (<1MHz) and has longer range (up to several kilometers). Its applications include power distribution automation and remote meter reading. Nowadays due to the increasing demand of high speed data transmission networking in homes, offices and industrial buildings broadband PLC has found acceptance as a last-mile solution for Internet distribution and home networking. Broadband PLC works at higher frequencies (>1MHz) and is suitable for shorter-range applications. To understand and utilize the characteristics of PLC and to provide good Quality of Service (QoS), it is inevitable to have knowledge about the channel characteristics which helps in modeling the channel so as to overcome the problems and challenges offered by this medium.

There are many techniques existing in literature to model a power line channel. The two approaches are: top-down approach and bottom-up approach. In top-down approach model parameters are obtained from measurement results, which make this approach prone to measurement errors. On the contrary, bottom-up approach involves formulation of the parameters which helps in obtaining an accurate model. This makes it versatile since the changes occurring in the channel transfer function or channel response due to changes in the system configuration can be predicted. It requires knowledge of the network topology, cables and loads. These approaches can be realized in a multipath environment in which an echo model can be developed to sum up all the multipath signal propagations or the power line network can be presented as a cascade of sub networks described using its network transmission matrices which contains information of the topology and terminal loads [1].

The standards for BPL include IEEE 1901, G.hn (Gigabit Home Networking), HomePlug 1.0, HomePlug AV and HomePlug AV2 specifications from HomePlug Power Line Alliance etc. IEEE 1901 standard uses transmission frequencies below 100 MHz which can be used by all classes of BPL devices, including BPL devices (<1500m to the premises) used for the connection to Internet access services as well as BPL devices used within buildings for local area networks. The latter describes a PLC system operating at 200 Mbps and is built upon OFDM FFT based physical layer utilizing frequency band of 1.8 – 30MHz.

This paper is organized as follows. In Section II PLC channel modeling by taking into account adjacent nodes of the network is carried out for a topology determined from a floor plan. For the PLC channel response obtained analysis based on a BPLC system with OFDM is carried out. In Section III a typical model of home networking is taken for the study and FTW Simulator [2], [3] is used for the analysis. Simulation results are provided and discussed in Section IV. Finally, conclusions are summarized in Section V.

II. Modeling the PLC Indoor Channel

The power transmission line is a harsh environment for the high-frequency communication signals which makes the channel modeling very difficult. Even though tremendous efforts have been proposed to determine accurate channel models for power lines, there is no universally accepted model. One of the technical problems includes different noises which have to be dealt by noise modeling of the PLC channel. The model considered in this paper is free from the disturbances. Here the time-domain approach of computing the channel response by summing up the multipath signal propagations is considered. The effect of adjacent nodes on channel response is also taken into account. Using this method the channel responses of the arbitrary channel links of an in-building network under study can be calculated.

A. General Purpose Indoor BPLC Channel Modeling

In a network, signals reach the receiving end by travelling in a direct path called the Line-Of-Sight (LOS) and also indirectly received due to impedance mismatches in the path which is called the obstructed (OBS) path. The sum of these LOS and OBS signals will describe the multipath signal propagations. Consider the indoor power line topology as shown in Fig. 1.

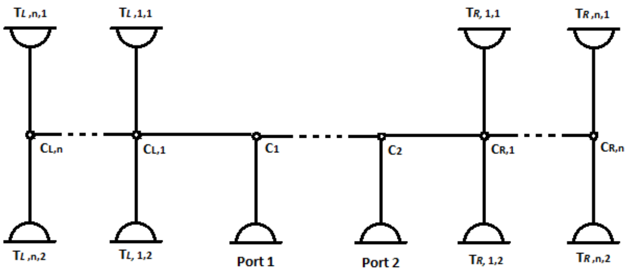

Fig. 1. A power line network with *n* adjacent nodes not coming in the direct path of Port 1 and Port 2. *C* and *T* indicate the nodes (internal junctions) and the terminals respectively [2].

Taking into account the effect of multipath signal components reflected from adjacent nodes as well, the channel response is given by

$$H(f) = D(A_L + 1)(A_R + 1) \tag{1a}$$

$$A_L = LOS_{L,1} + OBS_{L,1}\left\{\prod_{k=1}^{K_{L,1}}\left(S_{L,1,1}+1\right)-1\right\} \tag{1b}$$

$$A_R = LOS_{R,1} + OBS_{R,1}\left\{\prod_{k=1}^{K_{R,1}}\left(S_{R,1,1}+1\right)-1\right\} \tag{1c}$$

where A_L and A_R are the sum of multipath signal propagations on the left-hand side of Port 1 and the right-hand side of Port 2, respectively. If there are no adjacent nodes on the right-hand side of Port 2 and on the left-hand side of Port 1, then $A_R = 0$ or $A_L = 0$, respectively. D is the channel response of direct path. $LOS_{L,1}$ and $OBS_{L,1}$ are the signals in the left- hand side of the Port 1 and $LOS_{R,1}$ and $OBS_{R,1}$ are the signals in the right-hand side of the Port 2. $S_{L,1,1}$ and $S_{R,1,1}$ are the sum of the reflected signals, described by infinite geometric series. $K_{L,1}$ and $K_{R,1}$ are the number of branches on the first adjacent node to the left-hand side of Port 1 and the right-hand side of Port 2, respectively. This calculation reduces the complexity since the distant nodes are not considered as they hardly affect the channel response [4].

B. Channel Modeling of a power line network topology based on Section II-A

The channel modeling in Section II-*A* was developed and verified according to Meng's echo model [5]. If attenuation of the signal along the path is also added up, the channel response will be

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

where the weighting factor g_i is a product of transmission and reflection factors for the i^{th} path, τ_i is the delay of the path

$$\tau_i = \frac{d_i}{v_p} \tag{3}$$

calculated from d_i - length of the transmission paths for various path numbers and v_p - propagation velocity . N is the total number of paths , a_0 and a_1 are the attenuation parameters and k is the exponent of the attenuation factor [6],[7].

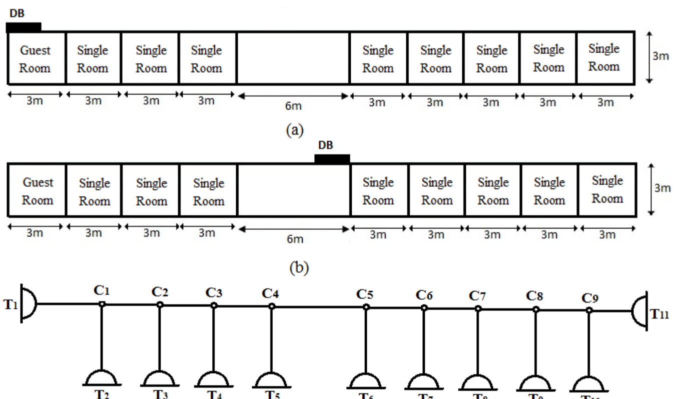

Fig. 2. (a) A floor plan of a building with DB placed at the corner of the floor, (b) DB placed at the centre of the floor and (c) the network topology of the floor plan with internal junctions and terminals indicated by C and T respectively. The lengths between C's and from C to T are fixed as 3m and 1.5m respectively. Length between C_4 and C_5 is set as 6m.

To investigate the channel response of network topology with adjacent nodes, an indoor power line network topology as shown in Fig. 2 (c) is considered. The topology is developed from an example of a wiring in a floor plan used for a ground floor of a hostel building. As shown in Fig. 2 (a) and Fig. 2 (b) the topology have Derivation Box (DB) from which connections or wiring is drawn to the outlets (OL) or terminals. Apart from the effect of cable characteristics and the load impedances in the network, the line length from DB to outlets has an impact on the channel response. Table I shows the simulation parameters.

TABLE I. SIMULATION PARAMETERS

Parameter	Value considered
Exponent of attenuation parameter, k	1
Attenuation parameter, a_0	0
Attenuation parameter, a_1	7.8 x 10^{-10} s/m
Number of signal paths, N	4

Software simulation was carried out in MATLAB based on the model according to Eq. 1 and Eq. 2 to obtain the transfer function whose amplitude response and phase response are as shown in Fig.3 and Fig.4 for both the cases.

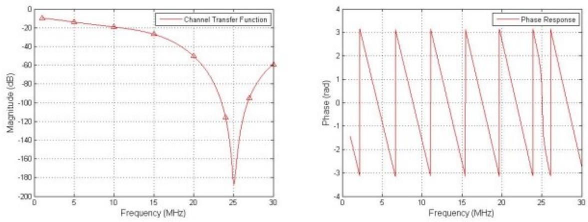

Fig.3 Calculated channel response and phase response for the network topology in Fig.2 (a).

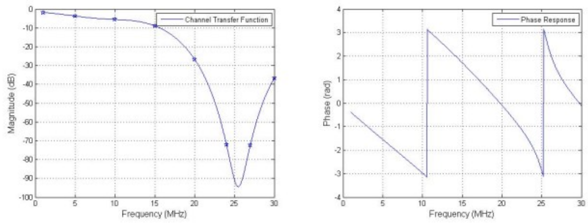

Fig.4 Calculated channel response and phase response for the network topology in Fig.2 (b).

Fig. 3 shows the channel response for the PLC network in Fig. 2 (a) in which the line lengths from DB to outlets is longer than the line lengths of DB to outlets in network topology shown in Fig. 2 (b) for which the channel response is as shown in Fig. 4. The attenuation notches in the channel response can be utilized in designing to predict the system performance for different network configurations. For instance, at 20 MHz the attenuation for longer line lengths from DB to OL is -50dB whereas for the shorter line lengths the value is -26dB. The result also shows that at frequency 25 MHz, with deep notch in the transfer function, the phase response have a non-linearity indicating delay which leads to phase distortion. Thus it can be interpreted from the channel responses in Fig. 3 and Fig. 4 that by modeling the network topology one can obtain better performances in channel modeling. Further investigation will be done on this and is described in Section IV.

C. A BPLC System with OFDM

The developments in multi-carrier based techniques such as Orthogonal Frequency Division Multiplexing (OFDM) enables the transmission of high data rates and provides the ability to cope with severe channel conditions. Its increasing interest has made it a preferred modulation for PLC. Fig. 5 shows a block diagram of a BPLC system with OFDM. First an input binary data stream is converted from serial to parallel and then undergoes modulation. The conventional mapping scheme BPSK is used. Number of subcarriers used is 100. After the modulation, the parallel sub-channel data undergoes Inverse FFT (IFFT) which generates OFDM signals. Cyclic prefix is added and converted to serial data which is fed to the PLC channel. On the receiver side the signal received is processed to remove the cyclic prefix and Fast Fourier Transform (FFT) is carried out. Demodulation of the sub-carriers extracts the data bits which when converted from parallel to serial gives the output of the system. The bit error rate (BER) performance of the system with PLC channel defined in Section II-B is evaluated. Fig. 6 shows the result for BER versus Signal to Noise Ratio (SNR) of the above system. It can be deduced

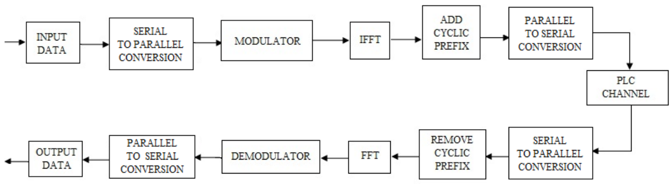

Fig. 5 A Block diagram of a BPLC system using OFDM.

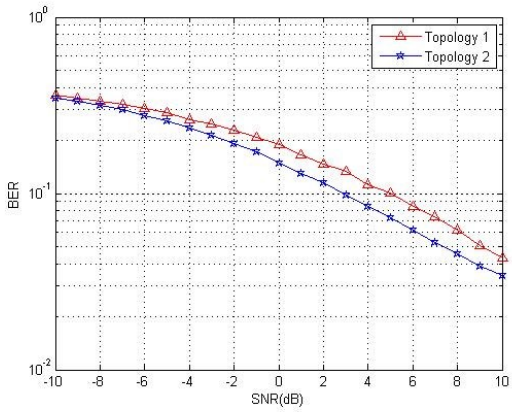

Fig. 6 BER Vs SNR plot for the OFDM BPLC system.

from the result that the topology with smaller line lengths of DB to outlets (topology in Fig. 2 (b)) provides better BER performance than the topology with greater line lengths of DBs to OLs (topology in Fig. 2 (a)).

III. PLC NETWORK TOPOLOGY FOR A TYPICAL THREE APARTMENT FLAT

The other channel modeling described in Section I includes describing the whole network behavior with transmission matrices. The representation of a power line network is made by the cascade connection of sub-networks which results in easy calculation of the channel response. By using ABCD or transmission matrices channel transfer function can be determined [8]. FTW PLC Simulator is used for this purpose. Bottom-up approach is followed to describe the network topology. It enables one to specify the network topology description involving the connection between the Service Panel (SP) and the Derivation Boxes (DB) and outlets (OL). Simple as well as complex topologies having large number of DBs and OLs can be dealt with this simulator.

For the analysis a power line network topology as illustrated in Fig. 7 is taken for study. This particular topology under consideration is a three apartment floor plan, in which the apartments are indicated by A, B and C. It contains three

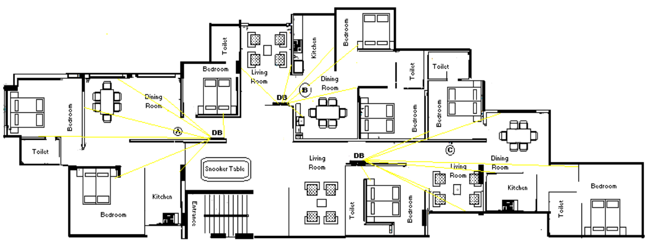

Fig. 7. An example model for last-mile power line network topology.

DBs which are connected to a SP. Star Type connection is used to connect the DBs to the OLs. The simulator is used in fixed mode in which topology and all the parameters are fixed. All the network specifications like the number of DBs, type of cable based on its cross-section, line length of cables used to connect from SP to DBs and DBs to outlets and impedances (if any) connected to the OLs should be defined. Two end-points are chosen as Transmitter and Receiver and 100Ω is the value taken for both source and load impedance. The cable sections used for this study are 1.5mm and 2.5mm, since cable types greater than these values are not widely used for home networking [9].

IV. RESULTS AND DISCUSSION

The network topology 1 with three DBs each having a provision of six or seven outlets is created as shown in Fig. 8 from the model represented in Fig. 7 using the simulator. Another topology 2 with smaller line lengths from DBs to OLs is also created for the comparison study as shown in Fig. 9. Two cases of impedance settings, namely, outlets without load (i.e., open circuit) and with load are considered for the computation of channel responses. The transmitter and receiver was fixed at 2nd DB 4th OL and 3rd DB 1st OL respectively. Fig. 10 illustrates the simulation result for the channel responses when all outlets are open circuited. The attenuation is less for topology 2 when compared to topology 1. At higher frequencies an improvement of 17 dB could be noticed for topology 2. So it can be deduced that as the line lengths from the DBs to OLs are shorter, better performance for the channel response is achieved. The same topologies are assigned with load impedances. In this case frequency selective impedances [9] were selected for some outlets and an open circuit is used by default if the impedance is not defined for any OL. Then the simulation result for the channel responses are shown in Fig. 11. The same inference is deduced in this scenario also. Also, it can be seen that the channel response changes as the load impedances assigned to the outlets vary.

A reconfiguration of the same network topology is made by increasing the number of DBs to six and dividing the outlets among these six DBs. The topology 3 with the line lengths is created as shown in Fig. 12. The transmitter and receiver was fixed at 4th DB 1st OL and 6th DB 1st OL respectively.

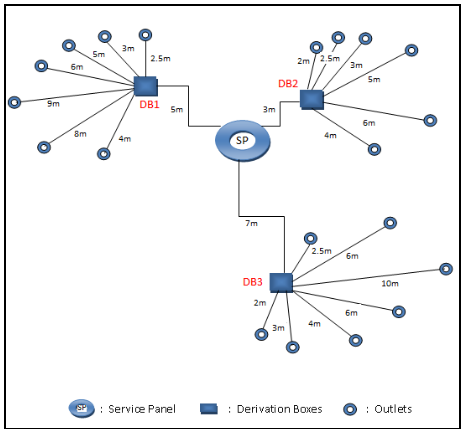

Fig. 8. Network topology1 for the apartment model in Fig. 7.

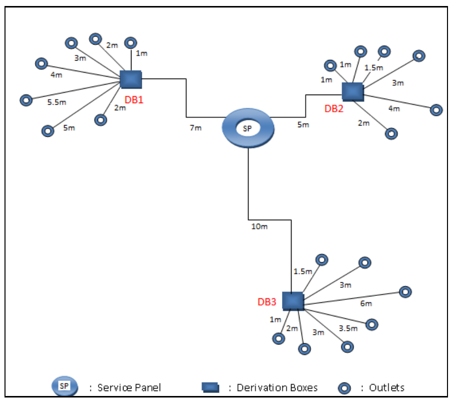

Fig. 9. Network topology 2 for the model in Fig. 7 with smaller line lengths from DB to OLs.

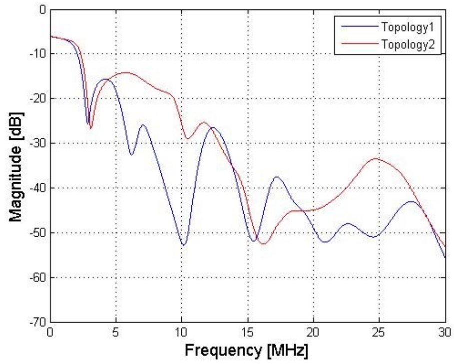

Fig. 10. Channel response for topologies in Fig. 8 and 9 with all outlets open circuited.

Simulation was carried out to see the change in channel response whether any improvement in performance could be obtained by increasing the number of DBs. The simulation result in Fig. 13 illustrates the comparison for the channel responses of these three topologies. All the OLs were left open circuited. For instance at 25MHz, the attenuation of topology 3 has an improvement by 13dB with topology 1 and a decrement of 3dB with topology 2.

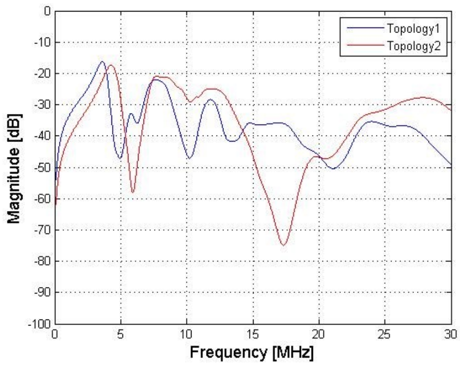

Fig. 11. Channel response for topologies in Fig. 8 and 9 with loads specified at some outlets.

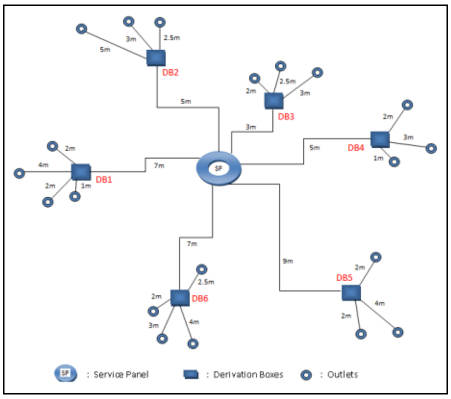

Fig. 12. Network topology 3 for the model in Fig. 7 with number of DBs equal to six.

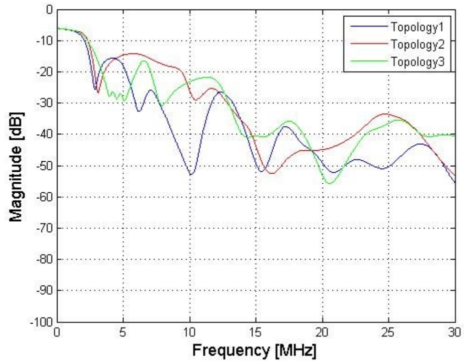

Fig. 13. Channel response for topologies in Fig. 8, 9 and 12 with all outlets open circuited.

So the channel response of topology 3 has better performance than topology 1 whereas its performance is comparable with the topology 2. However, the channel response varies with different loads at the OLs. Thus the topology with smaller line lengths from DB to OLs can bring out better performance in BPLC networks.

For the network topology 1, the position of transmitter and receiver is varied to observe the effect on channel response. The transmitter and receiver was fixed at 2nd DB 4th OL and 3rd DB 1st OL respectively in the 'far' case and 2nd DB 1st OL and 2nd DB 4th OL in the 'near' case. The simulation result in Fig. 14 illustrates that at higher frequencies the attenuation for the 'near' case has an improvement of almost 31 dB compared with the 'far' case. Thus it can be deduced that when the receiver outlet is near the transmitter outlet, the channel response exhibits a far better result. In such a case the channel is reliable and provides an acceptable performance.

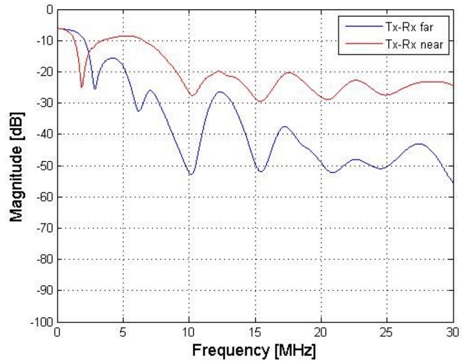

Fig. 14. Channel response for topology in Fig. 8 when distance between transmitter and receiver is varied.

V. CONCLUSION

The importance of modeling network topology in BPLC is investigated. PLC channel response for a typical indoor home network is analyzed. Study on the effect of network topology on channel response is carried out in this paper by varying the distance between DBs to OLs with load and without load scenarios. As this line length is shorter better performance results can be obtained. It had a comparable result with increased number of DBs and the same can be investigated further for a larger and complex network topology. The transceiver location points and altering the distance between them to provide better data rate is also observed. It is deduced that the PLC devices placed on the outlets located closer to the Internet input connection in the building can be used for receiving the Internet-flow with a satisfactory coverage. Thus, BPLC has the potential to become an effective means for last-mile delivery of broadband services.

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