

Transfer Function and Impulse Response Simulation of Power Line Channel

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Abstract: Due to increasing complexity, space and cost of communication network, the Electric Power Network has been considered a great option for the solution of all problems. Power line communications (PLC) term stands for the technologies for the data communication over the electrical power supply network. Existing power system is not designed for having data transfer. In this paper we have developed a simulation model of power-line for low voltage distribution network in home. Impulse response of the channel is generated in order to characterize the behavior of power line channel for high speed data communication purpose. To represent Multi-branch network mathematically, ABCD matrix parameters are used. Load mismatching is experimented on three parameters multiple loading, multi-branch and different cable length and analysis is presented of its effect on impulse response. All the simulation work has been done using MATLAB.

Keywords: Power line communication, Channel modeling, Impulse response, High speed data.

1. Introduction

The Electric Power and communication is the backbone of modern society and it is a crucial ingredient for economic growth and prosperity for every nation and the people it supports. We know the Electricity is consumed in everything and it has become synonymous with life in the industrialized and Globalise world. The power line has very huge infrastructure, so if we use this infrastructure for communication purpose like internet, power line data transmission, control command etc. it will be great utilization of the resource. The power-line communications (PLC) has been applied as a data transfer method in both public electricity distribution networks and indoor distribution networks. The devices designed for the purpose of Broadband internet, High speed data communication or controlling commanding the power devices etc. at home and industries. During the last years the conception of providing broadband Internet access through a low voltage distribution network has aroused a hot discussion. The characteristics of power-line channels and the applicability of different digital modulation techniques have been widely researched, because it make the power line more efficient and reliable communication. Power line communications (PLC) systems transmit data over conductors designed and used for electric power transmission. In the beginning PLC systems have shown limited applications, since they only supported low data rate. However, it has recently been how the PLC systems can be used to provide high-speed data rate by using a bandwidth up to 100 MHz as defined in the G.hn standard [1]. The power line channel is a very harsh and noisy transmission medium that is very difficult to model [2], since it is frequency selective, time-varying and impaired by coloured background and impulse noise. The time-variation of the channel arising from running appliances connected to the network allow to represent the overall power line channel as a linear periodically time-varying (LPTV) system synchronized with the mains. The channel can be seen as a periodical series of channels which result in a linear time invariant (LTI) behaviour. An interesting property of the PLC channels has been presented in [3] where the problem of determining the exact conditions under which the power

line channel may be considered as a symmetric channel has been addressed. The modelling of power line as a communication channel is addressed in [4], where its Transfer Function for the multipath communication is derived using the chain matrix method. In order to ascertain this transfer function, the author used parameters like propagation constant and characteristic impedance in a lumped-element circuit model by approximating the channel as a two-wire transmission medium. In another approach the power line is modelled as a Communication channel with two customary parameters, namely, characteristic impedance and propagation constant using the lumped-element circuit model once again [5]. Here the authors have derived the transfer function for an N- branch power line communication channel based on the scattering matrix method.

In this paper we modelled a domestic power line network as a communication channel using ABCD matrix for high speed data communication and also finding the channel transfer function, impulse response of simulated s-parameter of the channel using MATLAB and also investigate the effects of different loads and different length of the channel. This work is based on the simulator [6] and papers [7], [8], [9], [10] and [11].

2. Proposed work

The simplified network layout proposed in this work can be observed in Figure.1, It contains five derivation boxes (DB), which are directly connected to the service panel (SP). Two different types of connections (star and bus) are used to connect outlets to derivation boxes and the connection between the energy provider and the house is done through the service panel (SP). Several derivation boxes (DBs) are present in the home network topology and each of these is directly connected to the SP.

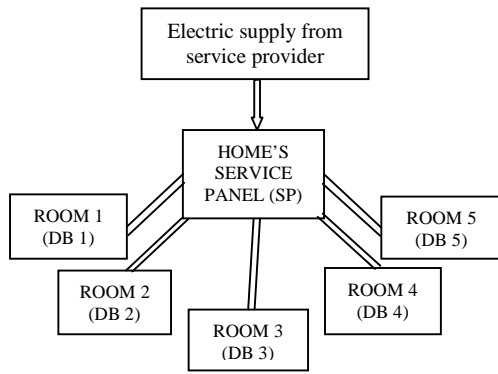


Figure 1: Power line network in home

Each power line section that starts from the DB and terminates into an outlet (OL) and load is always connected at OL. We have defined two different types of connections between the outlets (OL) and derivation boxes (DB) a STAR connection (SC) and a BUS connection (BC) as shown in figure 2 and 3 respectively

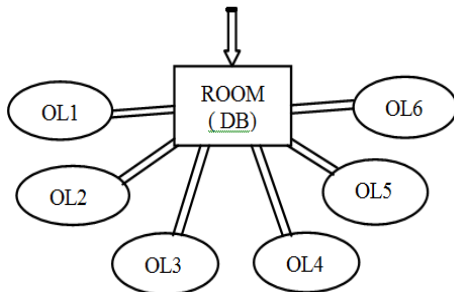


Figure 2: Star network connection at DB

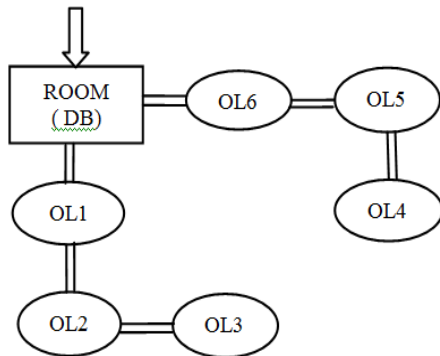


Figure 3: Bus network connection at DB

In a SC each outlet (OL) is directly connected to a DB as shown in figure 3. In a BC the outlets (OL) are connected in parallel to a DB as shown in figure 3. In this proposed network connect a star connection at derivation boxes DB1, DB3, DB4 and bus connection at derivation boxes DB2, DB5 used.

2.1 Cable Models

In a frequency range up to 30 MHz the characterization of power line parameters is challenging. One approach is to define the cable parameters depending on the physical realization of the cable and on its physical dimensions. Another approach is to estimate the primary cable parameters R, L, G, and C (resistance, inductance, conductance and capacitance per unit length) based on the secondary parameters, the propagation constant γ and the characteristic

impedance Z_c . In this work, transmission line parameters R, L, G, and C has been derived from the data of typical electrical-cable manufacturers (see Table 1). It is possible to choose among five cable types with sections from 1.5mm up to 10mm, but usually cable section greater than 4mm are not used for in-home connect.

Table 1: Electric cable data sheet

| Cable type | 0 | 1 | 2 | 3 | 4 |
|----------------------------|------|------|------|------|------|
| Section (mm ²) | 1.5 | 2.5 | 4 | 6 | 10 |
| ϵ_{eq} | 1.45 | 1.52 | 1.56 | 1.73 | 2 |
| $Z_c(\Omega)$ | 270 | 234 | 209 | 178 | 143 |
| C(pF/m) | 15 | 17.5 | 20 | 25 | 33 |
| L(μ H/m) | 1.08 | 0.96 | 0.87 | 0.78 | 0.68 |
| R_0 | 12 | 9.34 | 7.55 | 6.25 | 4.98 |
| G_0 | 30.9 | 34.7 | 38.4 | 42.5 | 49.3 |

Characteristics of actual indoor power network cables.

$$R = R_0 10^{-5} \sqrt{f} (\Omega/m), G = G_0 l 10^{-14} 2\pi f (S/m)$$

Where, f represents the frequency in [MHz]

2.2 Impedance models

Characterization of impedances is crucial in the PLC channel modelling. When appliances are connected to the outlets, their influence on the channel performance is twofold. First, they considerably affect the frequency response and input impedance of the channel and second, they will partially determine the level of background noise.

Appliances behaviour can be classified in three groups:

- (a) Approximately-constant impedances,
- (b) Time-invariant frequency-selective impedances.
- (c) Time-varying and frequency-selective impedances.

In this work of PLC Simulator we are going to consider only the approximately constant impedances and the time invariant frequency-selective impedances.

Approximately-constant impedances are: (a) Low impedance: 5 Ω , (b) RF standard impedance: 50 Ω , (c) Impedance similar to transmission line Z_c : 150 Ω , (d) High impedance: 1000 Ω , and (e) open circuit impedance: ∞

A parallel RLC resonant circuit has been presented in [12] as an adequate model for the frequency-selective impedances. The impedance model is defined as:

$$Z(\omega) = \frac{R}{1 + jQ \left(\frac{\omega - \omega_0}{\omega} \right)}$$

where, R represents the resistance at resonance, ω_0 the resonance angular frequency, and Q the quality factor which determines the selectivity.

Table 2: Frequency dependent impedances

| Impedance | R(Ω) | Q | $\omega_{0/2\pi}$ MHz |
|----------------|------|----|-----------------------|
| Z ₁ | 863 | 6 | 2.7 |
| Z ₂ | 394 | 34 | 10.7 |
| Z ₃ | 1312 | 9 | 10.07 |

The typical values of R, ω_0 and Q are reported in Table 2 for the sake of completeness. Finally, for the source impedance Z_S and the load impedance Z_L we are going to consider a common value of 100Ω.

3. Transfer Function

The channel transfer functions (H(f)) is defined from the theory of two-port network model[13], the channel transfer functions (H(f)) is defined as the voltage ratio between load voltage V_L and source voltage V_S (see Figure 4) by:

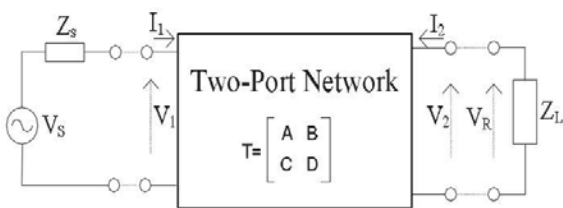


Figure 4: PLC Two port network model

Figure 4 depicts a simple power line channel model and we can define relations between V₁, I₁, V₂, and I₂ (the input and output voltage and current of a two port network, respectively) as:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}$$

The parameters A, B, C and D are frequency dependent components. The above expression can be easily used to calculate useful quantities such as the input impedance and the transfer function of the communication channel.

$$V_1 = A V_2 + B I_2 \quad (1)$$

$$I_1 = C V_2 + D I_2 \quad (2)$$

Transfer Function: $H(f) = \frac{V_L}{V_S} \quad (3)$

$$V_L = V_2 = I_2 Z_L \quad (4)$$

$$V_S = I_1 Z_S + V_1 \quad (5)$$

Eq. (5) can be simplified further by substituting I₁ & V₁ with (1) and (2)

$$V_S = (C V_2 + D I_2) Z_S + A V_2 + B I_2$$

$$V_S = (C I_2 Z_L + D I_2) Z_S + A I_2 Z_L + B I_2 \quad (6)$$

Substituting the values of V_L & V_S in Eq. (3)

$$H(f) = \frac{V_L}{V_S} = \frac{I_2 Z_L}{C I_2 Z_L Z_S + D I_2 Z_S + A I_2 Z_L + B I_2} \quad (7)$$

$$H(f) = \frac{Z_L}{C Z_L Z_S + D Z_S + A Z_L + B} \quad (7)$$

$$H(f) \text{ in dB} = 20 \log_{10} \left| \frac{Z_L}{C Z_L Z_S + D Z_S + A Z_L + B} \right| \quad (8)$$

3.1 Transmission line modelling:

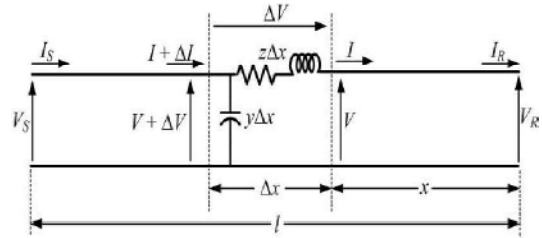


Figure 5: Transmission line modelling

The accurate modelling of the transmission line we must not assume that the parameters are lumped but are distributed throughout line. The single-line diagram of a long transmission line is shown in Figure. 5 The length of the line is l. Let us consider a small strip Δx that is at a distance x from the receiving end. The voltage and current at the end of the strip are V and I respectively and the beginning of the strip are V + ΔV and I + ΔI respectively. The voltage drop across the strip is then ΔV. Since the length of the strip is Δx, the series impedance and shunt admittance are z Δx and y Δx. It is to be noted here that the total impedance and admittance of the line are given below:

$$Z = z \times l \text{ and } Y = y \times l \quad (9)$$

$$\Delta V = I_z \Delta x \Rightarrow \frac{\Delta V}{\Delta x} = I_z \quad (10)$$

Again as $\Delta x \rightarrow 0$, from (10) we get

$$\frac{dV}{dx} = I_z \quad (11)$$

Now for the current through the strip, applying KCL we get $\Delta I = (V + \Delta V) y \Delta x = V y \Delta x + \Delta V y \Delta x \quad (12)$

The second term of the above equation is the product of two small quantities and therefore can be neglected.

For $\Delta x \rightarrow 0$ we then have

$$\frac{dI}{dx} = V_y \quad (13)$$

Taking derivative with respect to x of both sides of (11) we get

$$\frac{d}{dx} \left(\frac{dV}{dx} \right) = z \frac{dI}{dx}$$

Substitution of (13) in the above equation results

$$\frac{d^2V}{dx^2} - yzV = 0 \quad (14)$$

The roots of the above equation are located at $\pm\sqrt{(yz)}$. Hence the solution of (14) is of the form

$$V = A_1 e^{x\sqrt{yz}} + A_2 e^{-x\sqrt{yz}} \quad (15)$$

Taking derivative of (15) w.r.t. x we get

$$\frac{dV}{dx} = A_1 \sqrt{yz} e^{x\sqrt{yz}} - A_2 \sqrt{yz} e^{-x\sqrt{yz}} \quad (16)$$

Combining (11) with (16) we have

$$I = \frac{1}{z} \left(\frac{dV}{dx} \right) = \frac{A_1}{\sqrt{z/y}} e^{x\sqrt{yz}} - \frac{A_2}{\sqrt{z/y}} e^{-x\sqrt{yz}} \quad (17)$$

Let us define following two quantities

Characteristics impedance, $Z_c = \sqrt{\frac{Z}{y}} \Omega$

Propagation constant, $\gamma = \sqrt{YZ}$

Then (15) and (17) can be written in terms of the characteristic impedance and propagation constant as

$$V = A_1 e^{\gamma x} + A_2 e^{-\gamma x} \quad (18)$$

$$I = \frac{A_1}{Z_c} e^{\gamma x} - \frac{A_2}{Z_c} e^{-\gamma x} \quad (19)$$

Let us assume that $x = 0$. Then $V = V_R$ and $I = I_R$. From (18) and (19) we then get

$$V_R = A_1 + A_2 \quad (20)$$

$$I_R = \frac{A_1}{Z_c} - \frac{A_2}{Z_c} \quad (21)$$

Solving (20) and (21) we get the values of A_1 and A_2

$$A_1 = \frac{V_R + Z_c I_R}{2} \quad (22)$$

$$A_2 = \frac{V_R - Z_c I_R}{2} \quad (23)$$

For $l = x$ we have $V = V_s$ and $I = I_s$. Therefore replacing x by l and substituting the values of A_1 and A_2 in (18) and (19) we get:

$$V_s = \frac{V_R + Z_c I_R}{2} e^{\gamma l} + \frac{V_R - Z_c I_R}{2} e^{-\gamma l} \quad (24)$$

$$I_s = \frac{V_R + Z_c I_R}{2 Z_c} e^{\gamma l} - \frac{V_R - Z_c I_R}{2 Z_c} e^{-\gamma l} \quad (25)$$

We know that

$$\frac{e^{\gamma l} - e^{-\gamma l}}{2} = \text{Sinh } \gamma l \text{ and } \frac{e^{\gamma l} + e^{-\gamma l}}{2} = \text{Cosh } \gamma l$$

Equation (24) and (25) can be rewrite as

$$V_s = V_R \text{Cosh } \gamma l + Z_c I_R \text{Sinh } \gamma l \quad (26)$$

$$I_s = \frac{V_R \text{Sinh } \gamma l}{2 Z_c} + I_R \text{Cosh } \gamma l \quad (27)$$

The ABCD parameters of the long transmission line can then be written as:

$$A = D = \text{Cosh } (\gamma l) \quad (28)$$

$$B = Z_c \text{Sinh}(\gamma l) \Omega \quad (29)$$

$$C = \frac{\text{Sinh } \gamma l}{Z_c} \text{ mho} \quad (30)$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \text{Cosh } \gamma l & Z_c \text{Sinh } \gamma l \Omega \\ \frac{\text{Sinh } \gamma l}{Z_c} & \frac{\text{Sinh } \gamma l}{Z_c} \end{bmatrix} \quad (31)$$

Characteristics impedance:

$$Z_c = \sqrt{(R + j2\pi f \cdot L) / (G + j2\pi f \cdot C)} \quad (32)$$

Propagation constant:

$$\gamma = \sqrt{(R + j2\pi f \cdot L) \cdot (G + j2\pi f \cdot C)} \quad (33)$$

Where,

R – Resistance in per unit length (Ω/m) of conductors.

L – Inductance in per unit length (H/m) of conductors.

G – Conductance in per unit length (S/m).

C – Capacitance in per unit length (C/m).

With the knowledge of the per-unit length parameters of the transmission line we can calculate the ABCD matrix of wire section.

3.2 ABCD parameter calculation between Transmitter and Receiver:

LTI channels are calculated by means of a synthesis in the frequency domain. For this purpose, the layout given in Figure (6) is represented by the interconnection of multiple transmission lines then, according to the transmission line theory, each section of line is modelled as a two-port network, characterized by its ABCD parameter matrix. Finally, the input-output relation of the system, i.e., the frequency response, can be obtained by matrices manipulation.

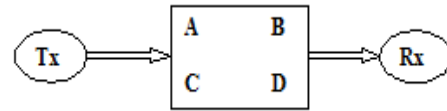


Figure 6: Equivalent ABCD parameter between Tx and Rx.

3.3 Relationship between ABCD to S-parameter:

Once the ABCD parameter is calculated between Tx and Rx then it has to be converted into S-parameter because it can easily characterize the frequency-domain behaviour of passive components and it can be used to calculate the Impulse response of channel. For example consider s-parameter of two port network.

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

Where, a_1 & b_1 are incident and reflected voltage at port-1, and a_2 & b_2 are incident and reflected voltage at port-2.

Conversion:

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} \frac{B - Z_n(D - A + CZ_n)}{B + Z_n(D + A + CZ_n)} & \frac{2Z_n(AD - BC)}{B + Z_n(D + A + CZ_n)} \\ \frac{2Z_n}{B + Z_n(D + A + CZ_n)} & \frac{B - Z_n(A - D + CZ_n)}{B + Z_n(D + A + CZ_n)} \end{bmatrix}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

$$= \begin{bmatrix} \frac{(1 + s_{11})(1 - s_{22}) + s_{12} s_{21}}{2s_{21}} & Z_n \frac{(1 + s_{11})(1 + s_{22}) - s_{12} s_{21}}{2s_{21}} \\ \frac{1 - (1 - s_{11})(1 - s_{22}) - s_{12} s_{21}}{2s_{21}} & \frac{(1 - s_{11})(1 + s_{22}) + s_{12} s_{21}}{2s_{21}} \end{bmatrix}$$

Z_n = Termination impedance of the port

3.4 Channel Impulse Response:

A linear time-invariant (LTI) system as shown in Figure (7) can be completely characterized by its impulse response ($H(\omega)$ or $h(t)$). Thus, for any input, the output function can be calculated in terms of the input and the impulse response.

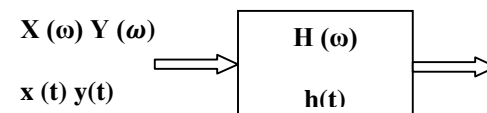


Figure: 7

The output function in time and frequency domain can be expressed as the following:

$$Y(\omega) = H(\omega) X(\omega) \quad (34)$$

$$y(t) = h(t) * x(t) = \int_{-\infty}^{+\infty} h(t - \tau) x(\tau) d\tau \quad (35)$$

The impulse response $h(t)$ of a system can be generated from its S-parameters by using inverse Fourier transform

$$h(t) = F^{-1}\{S(\omega)\} \quad (36)$$

In this work the channel S-parameters are produced by the calculated ABCD parameter of given network and the impulse response of the channel is calculated through MATLAB that represents the channel response characteristic.

3.4 Generating an Impulse Response from S-Parameters:

- Perform the inverse Fourier transform on the s-parameter of interest:
 $h(t) = F^{-1}\{S(\omega)\}$
- For ifft, produce negative frequency values and append to s-parameter data in the following manner
 $S(-f) = S(f)^*$
- Could perform ifft now, but will get an impulse response with time resolution of
 $\frac{1}{2f_{max}} = \frac{1}{2(30\text{ Mhz})} = 16.67\text{ ns}$
- For 1ns resolution: zero pad to +/-500MHz i.e 1 ns
- To improve impulse response resolution expand frequency axis and “zero pad” form +/- 500 MHz
- Now perform ifft to produce impulse response

4. Simulation and Results Analysis

In this section we show and analyze some results carried out by the PLC simulator. The network topology is defined as described in previously and the result is obtained in a fixed mode. For the fixed mode, we need to define all the network elements: the number of derivation boxes (DBs), line length from service panel (SP) to each DBs, and the used cable types. For each DB we specify the number of outlets (OLs), the connection type, and the cables used to connect OLs to DB. Furthermore, it is needed to specify the impedance connected to each OL otherwise an open circuit will be used by default. The transfer function and impulse response are obtained by modelling different power line communication channels using different cable lengths, different loading conditions. All cables used in the model are considered in table 1. The channel models are realized by using MATLAB scripts to code the channel parameters and equations. The transfer function plots for the different configurations are shown between the frequency bands 100 kHz - 30MHz. The Transmitter (Tx) are connected at DB1, OL1 and Receiver (Rx) are connected at DB3, OL1 point and remaining OL is used to connect the load impedance.

Case 1:

- All the OL terminals are Open circuited.
- SP to DB length = 2m
- DB to OL length = 2m

The transfer function $H(f)$ and Impulse response $h(t)$ shown figure 7 to 19.

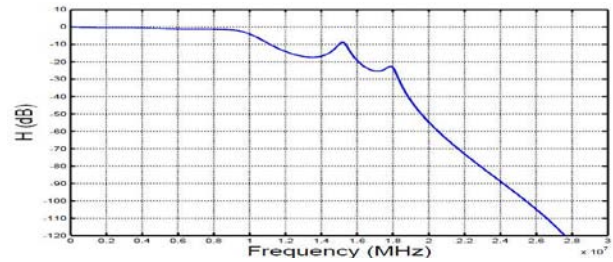


Figure 7: Transfer function of Power line Channel for DB-2m, OL-2m, OL-Open circuit.

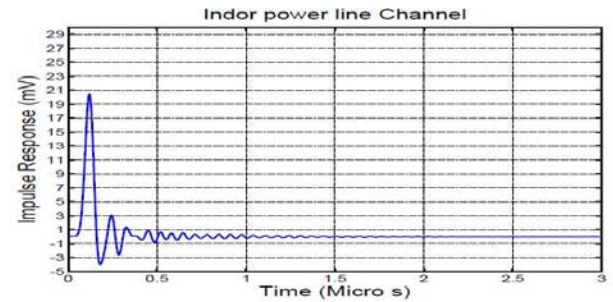


Figure 8: Impulse response of Power line channel for DB-2m, OL-2m, OL-Open circuit.

- All the OL are Open circuit.
- SP to DB length = 10m
- DB to OL length = 10m

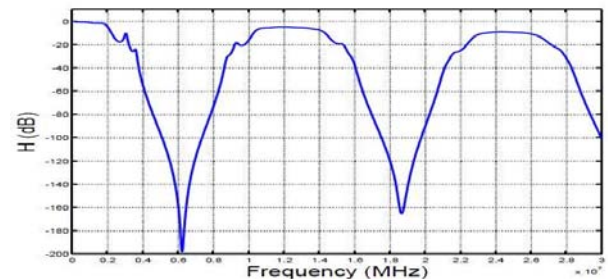


Figure 9: Transfer function of Power line Channel for DB-10m, OL-10m, OL- open circuit.

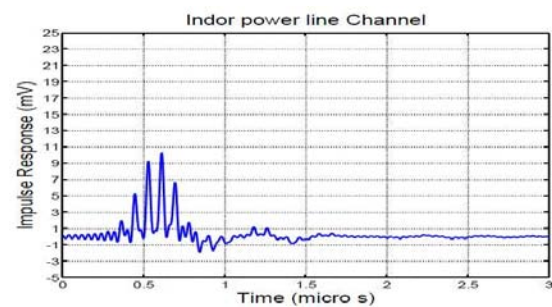


Figure 10: Impulse response of Power line channel for DB-10m, OL-10m

Case 2:

- All the OL are terminated by High impedance.
- SP to DB length = 2m
- DB to OL length = 2m

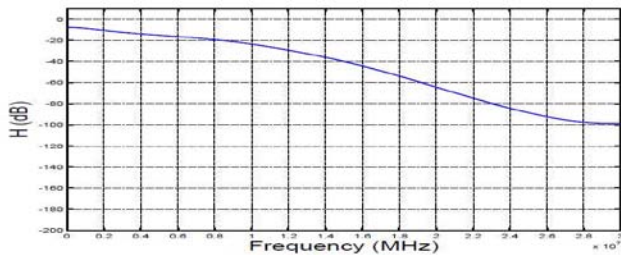


Figure 11: Transfer function of Power line Channel for DB-2m, OL-2m, OL-High impedance

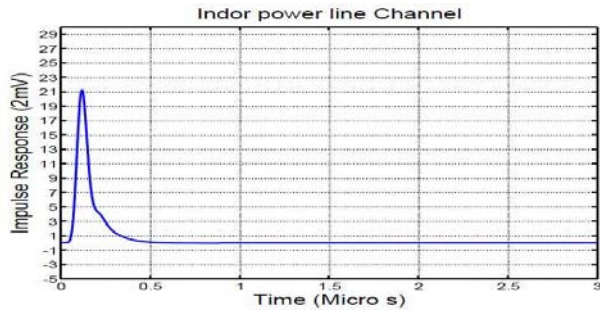


Figure 12: Impulse response of Power line channel for DB-2m, OL-2m, OL-High impedance

- All the OL terminated by high impedance.
- SP to DB length = 10m
- DB to OL length = 10m

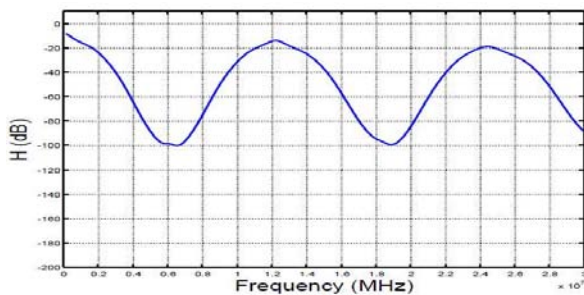


Figure 13: Transfer function of Power line Channel for DB-10m, OL-10m, OL-High impedance

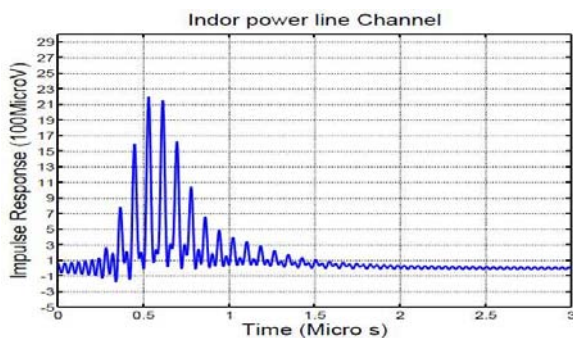


Figure 14: Impulse response of Power line channel for DB-10m, OL-10m, OL-High impedance

Case 3:

- All the OL terminated by RF impedance
- SP to DB length = 2m
- DB to OL length = 2m

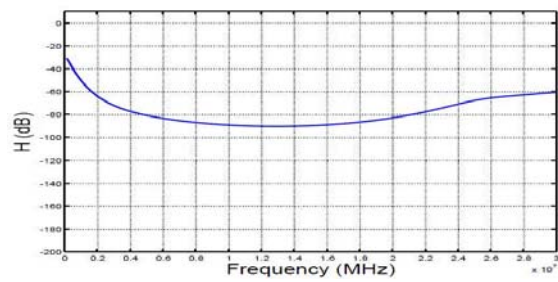


Figure 15: Transfer function of Power line Channel for DB-2m, OL-2m, OL-RF impedance.

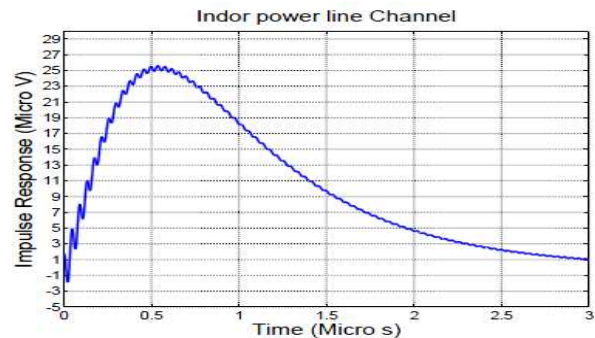


Figure 16: Impulse response of Power line channel for DB-2m, OL-2m, OL-RF impedance

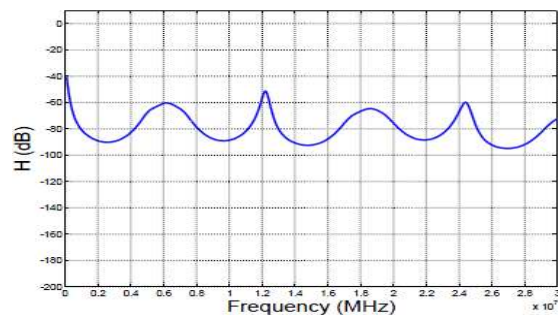


Figure 17: Transfer function of Power line Channel for DB-10m, OL-10m, OL-RF impedance.

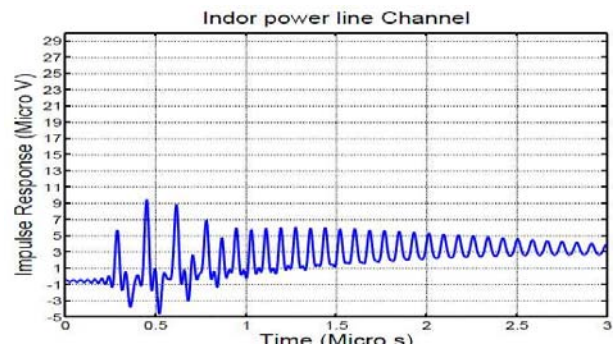


Figure 18: Impulse response of Power line channel for DB-10m, OL-10m, OL-RF impedance

5. Result Analysis and Conclusion

In this paper the modelling of a Low voltage power line network as communication channel for high speed data communication and a multi-branch power line communication channel is thoroughly explained using the ABCD matrix approach. The transfer function model of the communication channel and also find the impulse response of simulated channel using MATLAB and the effect of using different loading conditions, cable lengths and the efficiency

of the communication channel model is investigated which is given in Table:3

Table 3: Impulse response comparison for different length and load

| Load at OL | SP-DB (m) | DB-OL (m) | Impulse amplitude(μ v) | Impulse stable time(μ s) |
|------------|-----------|-----------|-----------------------------|-------------------------------|
| OC | 2 | 2 | 25000 | 0.2 |
| | 10 | 10 | 10500 | 0.75 |
| HIGH | 2 | 2 | 4250 | 0.3 |
| | 10 | 10 | 2250 | 1.0 |
| RF | 2 | 2 | 26 | 2.5 |
| | 10 | 10 | 10 | 3.0 |

- The results from the analysis shows that as increasing the cable length of the communication channel as a results increases the attenuation hence it decreases Impulse amplitude at receiver end.
- The analysis of result also shows that as increasing the cable length between Derivation Box(DB) to outlet (OL), it increases the pulse stable time of the communication channel and
- The increasing the load impedance at the OL it will cause increases the received pulse amplitude at the receiver end.

The output any LTI system can be achieve by convolution of input data with impulse response, the simulation of impulse response is the first phase of power line communication model. It will be used for performance research of different coding schemas, modulation and estimation techniques of high speed data transmission.

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