SIMULATION AND MATHEMATICAL MODELLING OF POWER LINE COMMUNICATION CHANNEL FOR HIGH DATA TRANSFER RATE

Nanik Ram Parhyar*, Madad Ali Shah*, Mir Mohammad Lodro*

ABSTRACT

Power Line Communication (PLC) is a technology where existing power lines are being used for communication purposes along with transmitting electrical signals. There are two types of PLC communication i.e. Narrowband PLC, which is used for lower frequency ranges from 9 KHz to 140 KHz, and it provides data rates up to 1000 bit per second (bps) and the other type is Broadband PLC, which uses higher frequency ranges from 2 MHz to 30 MHz and it can provide significantly higher data rates i.e. more than 2 Mbps. The data transfer bound on power lines is due to the existing power signals which create Electromagnetic Interference (EMI) with communication signals, and the other factor is non-linearity of the power line itself. Moreover, because of its time-dispersive nature, it creates frequency-selective fading effect which may give rise to Inter-Symbol Interference (ISI). The purpose of this research is to know that how the power lines behave when high frequency signals are transmitted on it, with the help of mathematical modelling and graphs of transmitted signal. In this context, the power-line is approximated as a two-wire transmission line, through which behaviour of the signals transmitted on PLC channel can be analysed. From the mathematical modelling perspective, it has been contributed that the amplitude and phase of transmitted signals are functions of distance and frequency. These signals are more distorted and attenuated with increasing frequency and distance. Finally, with the help of simulation results, it can be demonstrated that PLC performance is better at 30MHz in comparison to 40 MHz. From the simulation results, it can also be observed that as the frequency increases, more the signal is being distorted and attenuated. Therefore signals with higher frequencies have huge losses and phase of the signals remain linear.

Keywords: *PLC, Characteristic Impedance, Propagation Constant and Multipath.*

1. INTRODUCTION

Power lines provide harsh environment for high frequency communication signals [1] .One of the prominent errors may be multipath effects, which is produced due to impedance mismatch on PLC channel. PLC channel also contains different types of noise i.e. impulse noise, background noise, narrowband noise, and also the attenuation of transmitted signals [2-3]. Therefore, it becomes necessary to model the PLC channel. There are two approaches through which PLC channel can be modelled, one is multipath model and the second is transmission line approach [4]. In this research, two-wire transmission line theory is adopted. Power line applications are enormous, few of them are mentioned here including achieving load management [5], remote controlled appliances, home automation, intelligent buildings, remote distance meter reading in smart grids etc. Nowadays, smart girds are replacing classic grids with increased power management. Smart grid deployment requires significant contribution from communication engineers. Therefore, in smart grids the PLC is inevitable. Hence, in future high frequency signals will be transmitted over power lines. One of the biggest advantage of PLC is that the existing power line infrastructure may be used for both; the transmission of data and Power signals [5], and this ultimately saves the cost to avoid building a complete infrastructure. PLC modems are used to make communication in power supply networks. Data signals from conventional communication devices are converted by PLC modem in a form that is suitable for transmission over power lines [6].

These power transmission line systems are spread in a large geographical area and approximate power lines are spread to everyone’s home, therefore these persons will be able to receive broadband services without rolling over completely new infrastructure that is significantly costly. In addition to numerous advantages associated with the power lines there are disadvantages in the form of behaviour of the power lines, as the power lines are designed to carry the power signals at 60Hz frequency. Therefore, the power lines impose serious challenges to

* Department of Electrical Engineering, Sukkur Institute of Business Administration, Airport Road, Sukkur-65200, Sindh Pakistan. nanik.ram@iba-suk.edu.pk

the higher data transfer rates. The EMI and time depressiveness of the channel poses restriction on high data transfer rates. The power line communication can create ISI because of the frequency-selective fading nature, therefore requiring the need of advanced equalization techniques and contributing to complexity and cost. Fig. 2 shows approximated two-wire transmission line as tapped-delay line filter. As power line channel contains a lot of contaminations, recent work is carried on to mitigate these contaminations and to make the data transfer rates higher [1-2]. Moreover, Orthogonal Frequency Division Multiplexing (OFDM) can also be used to mitigate the ISI that may arise in power line communication channel. Since the PLC channel provides unfavourable environment for the telecommunication signals, it encodes the signal that is considered to be fundamental for data protection [7].This manuscript is divided in various sections i.e. research methodology is presented in section 2, broadband PLC channel modelling is part of section 3 which includes detailed transmission line and filter transfer function approach. Section 4 contains the simulation results and discussions and finally conclusions and future recommendations are given in section 5 and 6 respectively.

2. RESEARCH METHODOLOGY

Different research papers [1-10] were investigated thoroughly in order to get reasonable knowledge about PLC and sorted out what can be the research interest in the PLC. As a result it has been revealed that PLC channel causes huge distortion and attenuation to the signals which are transferred on PLC channel because of its nature. The power lines are made for transmitting energy signals whose frequency is much smaller than the communication signals. In order to transmit the higher frequency signals on the power line, it was necessary to study the PLC channel in detail. After rigorous research, it was revealed that there are two approaches of modelling the PLC channel i.e. multipath modelling and two-wire transmission line modelling [8], through which behaviour of the transmitted signals can be analysed. These approaches were scrutinized for requiring more information about the pros and cons of both techniques. By investigating it is known that Multipath approach is based on the reflections of signals from different branches because of impedance mismatching [9]. The multipath nature of power lines arise from the presence of several branches and impedance mismatch that causes the reflection of the signals [4]. This approach has two main disadvantages first is that because it becomes difficult to estimate delay, amplitude and phase associated with each path, it requires complex computations [10]. Secondly, it is a time domain approach, as all the paths from which reflections have occurred are taken into account and these paths complex in numbers, so this approach becomes complicated. However, multipath modelling can easily be applied for wireless channels. So depending on advantages and simplicity, two-wire transmission line has been selected to model PLC channel. By two wire transmission modelling, the behaviour of signals on power line communication channel can be analysed. During the research, it was also known that power lines have multipath effects. Finally, in this research, two-wire transmission line theory approach was adopted. As mathematical modelling was not enough to understand the behaviour of the signals completely therefore it was also necessary to show the graphical representation of behaviour of different signals. Hence some simulations were performed at various frequencies and the channel was considered as a two wire transmission line to show the true picture of signals. According to mathematical modelling, phase and magnitude response of the signals must also be simulated. For this purpose, the performance parameters which are magnitude response and phase response of signals, were simulated at different frequencies. It was again found that which software could help to show the magnitude and phase response of the transmitted signals at different signal considering channel as a two wire transmission line. It was also found that there is an RF tool box in MATLAB software in which parameters of two wire transmission line can be set and different responses like magnitude response and phase response can be simulated by setting different frequency ranges. Therefore the software that has been used for the simulation results is Math-work's MATLAB 7.0. In MATLAB the RF tool box helped to assess the performance parameters which are magnitude response and phase response. Those have been simulated at different frequencies by setting the parameters of two-wire transmission line channel.

3. MATHEMATICAL MODELLING

As there are two approaches of modelling PLC channel, depending upon some advantages as discussed above, the two wire transmission line approach is implemented in detail. In this approach, power transmission lines are modelled as two-wire transmission lines and by using scattering parameters the voltage and current at both input and output are related. Here two parameters i.e. propagation constant and intrinsic impedance are investigated. The intrinsic impedance of two-wire transmission line must stay constant to avoid impedance mismatch and reflections [8]. Through propagation constant which is imaginary number, the information is given about the phase shift constant and attenuation constant. By using two parameters i.e. intrinsic impedance and propagation constant, transfer function for PLC [11] or transmission matrices [12] can be obtained by using echo-based model. Equivalent circuit of two-wire transmission line is shown in Fig.1.

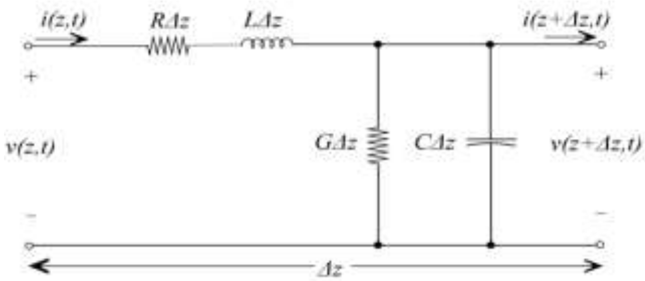

Figure-1. Equivalent circuit for two-wire transmission line

In Figure 1, i (z, t) and i (z +Δz, t) represent the currents at position z and z +Δz respectively, whereas v (z, t) and v (z +Δz, t) represent the voltages at position z and z +Δz respectively. R is series resistance per unit length (Ω/m) of the transmission line conductors; L is series inductance per unit length (H/m) of the transmission line conductors; G is shunt conductance per unit length (S/m) of transmission line conductors and C is shunt capacitance per unit length (F/m) of transmission line conductors.

By using the Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL) equations, the values of voltage and current are calculated at z and z+ Δ z.

$$v(z,t) - R\Delta z i(z,t) - L\Delta z \frac{\partial i(z,t)}{\partial t} = v(z+\Delta z,t) \quad (1)$$

$$\mathrm{i}(z,t) - G\Delta z v(z+\Delta z,t) - C\Delta z \frac{\partial v(z+\Delta z,t)}{\partial t} = i(z+\Delta z,t) \quad (2)$$

Taking the limit as Δ z $\rightarrow$ 0, the terms on the right hand side of equations above become partial derivatives with respect to z which gives

$$\frac{\partial v(z,t)}{\partial t} = -Ri(z,t) - L\frac{\partial i(z,t)}{\partial t} \quad (3)$$

$$\frac{\partial i(z,t)}{\partial t} = -Gv(z,t) - C\frac{\partial v(z,t)}{\partial t} \quad (4)$$

For time-harmonic signals, the instantaneous voltage and current may be defined in terms of phasor such that

$$v(z,t) = \mathrm{Re}\{\mathrm{V(z)}e^{j\omega t}\} \quad (5)$$

$$\mathrm{i}(z,t) = \mathrm{Re}\{\mathrm{I(z)}e^{j\omega t}\} \quad (6)$$

The derivatives of the voltage and current with respect to time yields jω times the respective phasor which gives

$$\frac{dV(z)}{dz} = -[R + j\omega L]I(z) \quad (7)$$

$$\frac{dI(z)}{dz} = -[\mathrm{G} + j\omega C]\mathrm{V}(z) \quad (8)$$

Differentiating both equations (7) and (8), we get the current and voltage equations as follows

$$\frac{d^2V(z)}{dz^2} = -\gamma^2 V(z) \quad (9)$$

$$\frac{d^2\,\mathrm{I}(z)}{dz^2} = -\gamma^2\,\mathrm{I}(z) \quad (10)$$

Equations (9) and (10) are called Telegrapher's equations which describe the voltage and current on transmission line with respect to distance and time. Where γ is the propagation constant of travelling wave on transmission line. Thus propagation constant of two-wire transmission line has been derived and is given below in equation (11), real part of propagation constant is attenuation constant and imaginary part is phase constant. Attenuation constant is defined as the rate at which amplitude of travelling wave is attenuated whereas phase constant is defined as the rate at which phase of travelling wave is changed:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (11)$$

The general solutions to voltage and current of telegrapher's equation are given below:

$$v(z) = V_0^+ e^{-\gamma z} + V_0^- e^{\gamma z} \quad (12)$$

$$\mathrm{I}(z) = I_0^+ e^{-\gamma z} + I_0^- e^{\gamma z} \quad (13)$$

In above equations superscript plus and minus indicate the travelling wave in +z and –z directions. By relating the general solutions with equations 7 and 8 we get:

$$\frac{V_0^+}{I_0^+} = \frac{V_0^-}{I_0^-} = \frac{R + j\omega L}{\gamma} \quad (14)$$

By replacing the γ, characteristic impedance can be found that is defined as the ratio of voltage to current of a travelling wave on the transmission line. Characteristic impedance expression as show in Equation (15) is obtained in the form of conductance, resistance, inductance and capacitance.

$$z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad (15)$$

The Transmission line parameters have been determined by using two-way transmission line model for PLC channel considering the type of conductor which is used. Equation (16) represents the resistance (R), conductance (G), and Equation (17) represents inductance (L) and capacitance (C) of a transmission line per unit length have been determined on which characteristic impedance depends

$$R = 1/\pi(\sqrt{\pi f \mu / \sigma}),\ G = \pi\sigma / (\cos^{-1}(\mathrm{D}/2\mathrm{a}) \quad (16)$$

$$L = \mu / \pi(\cos^{-1}(\mathrm{D}/2\mathrm{a})),\ C = \pi\varepsilon / (\cos^{-1}(\mathrm{D}/2\mathrm{a})) \quad (17)$$

3.1 TRANSFER FUNCTION

Whenever the signal is transmitted at the receiver end, it doesn't get one direct signal but get multiple signals with delayed versions. Because of impedance mismatching, the signals are reflected back and the PLC channel behaves like a multipath environment. Therefore the echo-model in Figure 2 is used to represent the different parameters of transmission line [8] and using this model, the transfer function of broadband PLC channel can be derived. The echo model shown in Figure 2 can be applied to model the PLC channel and the impulse response of the complete echo model is given in equation (18).

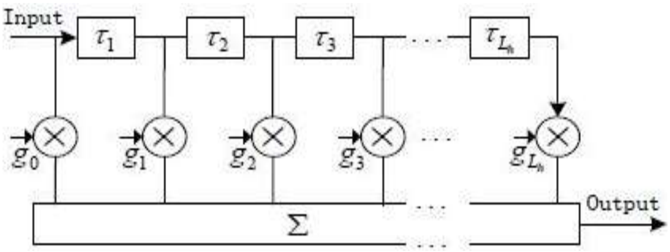

Figure-2. Echo Model of Power Line

$$h(t) = \sum_{i=1}^{N} g_i \delta(t - \tau_i) \quad (18)$$

Applying Fourier transform, the frequency response of echo model is shown in Equation (19):

$$H(f) = \sum_{i=1}^{N} g_i e^{-j\omega\tau_i} \quad (19)$$

In equations (18) and (19), gi is the attenuation factor of path i.

4. RESULTS AND DISCUSSIONS

In order to strengthen the concept of mathematical modelling the magnitude response and phase response of transmitted signals are simulated. In this section the simulations of PLC channel are performed. In the MATLAB software there is an RF tool which is used for execution of simulations. In simulation, the channel is considered as a two-wire transmission line in which different plots of magnitude response and phase response are simulated on different frequencies and are analysed. The channel is simulated on two different frequencies i.e. 30MHz and 40MHz.

4.1 Magnitude Response at 30MHz

Magnitude response shows how the magnitude of a signal behaves with respect to frequency when it is transmitted on a channel. For thorough understanding of magnitude response of a 30MHz signal two different scales are used i.e. linear scale and logarithmic scale.

4.1.1 Linear Scale Magnitude Response

In linear scale magnitude response both the x-axis and y-axis are kept linear. Frequency is kept as parameter of horizontal x-axis whereas magnitude is kept as a parameter of vertical y-axis. Scale of frequency is given in MHz. Fig. 3 shows the amplitude response of a signal transmitted on the channel in linear scale at 30MHz. S11 and S22 are the scattering parameters which are also called as reflection coefficient, these are checked during simulations. From the Fig. 3, it can be evaluated that the signal which is transmitted on PLC channel is distortion less as per equation (20). It can also be observed from Fig. 3 that the losses increases when the frequency is increasing.

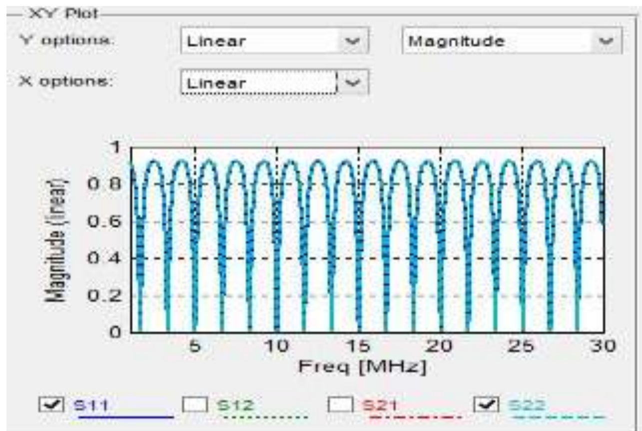

Figure-3 Magnitude Response of Linear Scale at 30MHz

Generally, it is expected that the transmission line should be distortion less within the required frequency [13]. A distortion less transmission line obtained can be modelled by following expression i.e. Equation (20).

$$H(\omega) = \begin{cases} ke^{-j\omega t_d} & \forall \omega \\ 0 & elsewhere \end{cases} \quad (20)$$

Similarly, the phase response of distortion less transmission line should be linear function of frequency over specified frequency.

4.1.2 Logarithmic Scale Magnitude Response

In logarithmic scale magnitude response, the x-axis is kept at logarithmic scale whereas y-axis is kept as logarithmic (dB). Frequency is kept as parameter of horizontal x-axis whereas the magnitude is kept as a parameter of vertical y-axis. The scale of frequency is given in MHz. Fig. 4 shows the amplitude response of a signal transmitted on the channel in logarithmic scale at 30MHz. S11 is the scattering parameter which is also called as reflection coefficient and is checked during simulations. In graph amplitude response is simulated according to S11 parameters. From the Fig. 4 it can be observed that at linear scale the signal which is transmitted on PLC channel is distortion less as per equation (20). It can also be perceived that there are dips at particular frequencies and the number of dips also increase as the frequency increases. These dips can cause the signal to be lost at particular frequency. These dips occur on PLC channel because of loads which are connected to the end terminals of power lines.

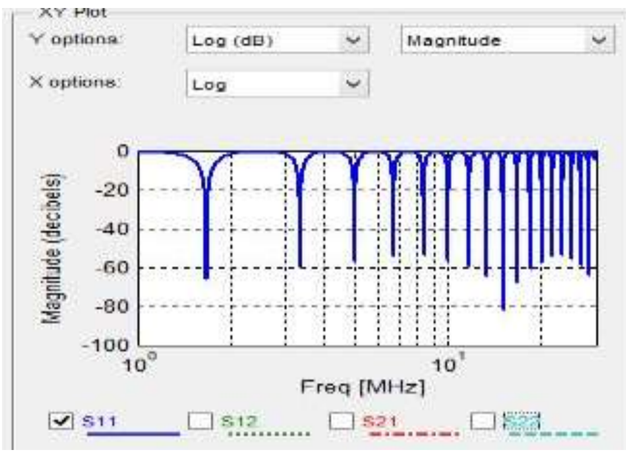

Figure-4 Magnitude Response of Logarithmic Scale at 30 MHz

4.2 Phase Response at 30 MHz

Phase response shows how the phase of a signal behaves with respect to frequency when it is transmitted on a channel. Frequency is kept as parameter of horizontal x-axis whereas phase is kept as a parameter of vertical y-

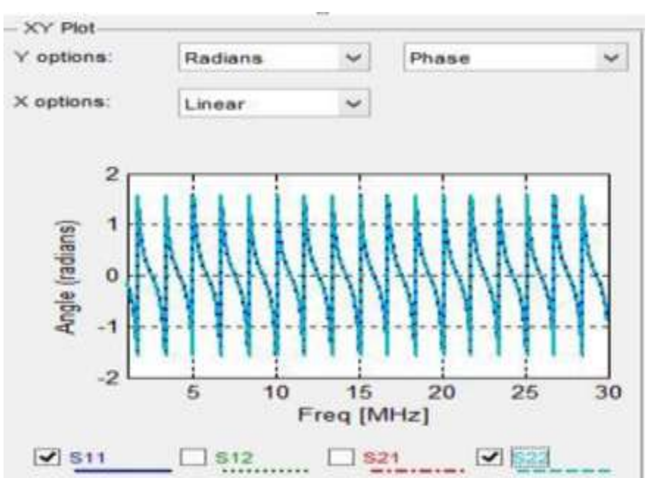

Figure-5 Phase Response at 30 MHz

axis. For the phase response of a signal, values on the x-axis are linearly related and the phase is measured in radians on y-axis.. Scale of frequency is given in MHz whereas phase in radians. Fig. 5 shows the phase response of a signal transmitted on the channel at 30MHz. S11 and S22 are the scattering parameters which are also called as reflection coefficients are checked during simulations. From the Fig. 5, it can be evaluated that the phase of the signal which is transmitted on PLC channel remains almost linear as the frequency increases. It can be said that phase of signal is not too much effected on PLC channel because the phase of the signal almost remains linear. Therefore the transmitted signals on PLC channel is distortion less as per equation (20).

4.3 Magnitude Response at 40 MHz

In this section the magnitude response of a 40 MHz signal is analysed using two different scales i.e. linear scale and logarithmic scale.

4.3.1 Linear Scale Magnitude Response

Here in linear scale, magnitude response of both the x-axis and y-axis are kept as linear. Frequency is kept as parameter of horizontal x-axis whereas magnitude is kept as a parameter of vertical y-axis. The scale of frequency is given in MHz. Fig. 6 shows the amplitude response of a signal transmitted on the channel in linear scale at 40MHz. S11 is one of the scattering parameters which is also called as reflection coefficient is checked during simulations. In graph amplitude response is simulated as per S11 parameters. From the Fig. 6, it can be evaluated that the signal, which is transmitted on PLC channel is more congested and have a severe distortion at 40 MHz scale. When magnitude response at 40 MHz is compared with the magnitude response of 30 MHz, signal having higher frequency, is more affected in the terms of distortion. The magnitude response of 40MHz also contain huge losses due to of the more dips which are less in the magnitude response of 30 MHz signals.

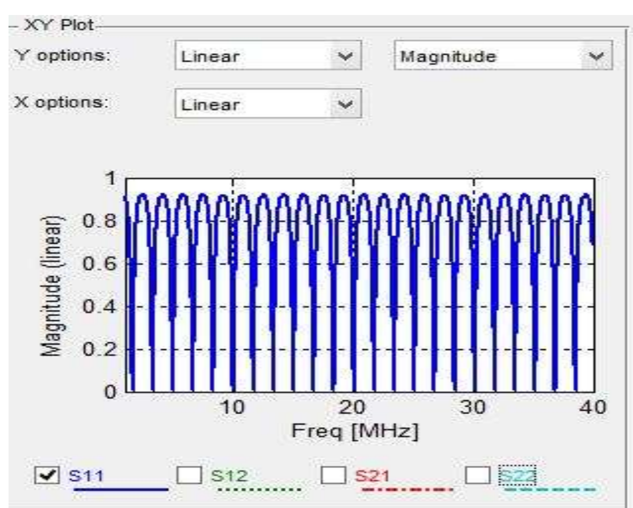

Figure-6 Magnitude Response of Linear Scale at 40 MHz

4.3.2 Logarithmic Scale Magnitude Response

In logarithmic scale the magnitude response x-axis is kept as logarithmic whereas y-axis is kept logarithmic (dB). Frequency is kept as parameter of horizontal x-axis whereas magnitude is kept as a parameter of vertical y-axis. Scale of frequency is given in MHz. Fig. 4 shows the amplitude response of a 40 MHz signal transmitted on the channel in logarithmic scale. S11 is the scattering parameter which is also called as reflection coefficient and is checked during simulations. In graph, amplitude response is simulated as per at S11 parameter. From the Fig. 7, it can be seen that there are huge dips in the magnitude response when 40 MHz signal is transmitted which causes the signals to be lost at particular frequencies. When magnitude response of 40 MHz signal is compared with the magnitude response of 30 MHz, the losses are higher in the magnitude response of 40 MHz signal. So it can be evaluated that signal having higher frequency are more affected by the loads, which are connected to the end terminals of power lines to incorporate more losses to the signals.

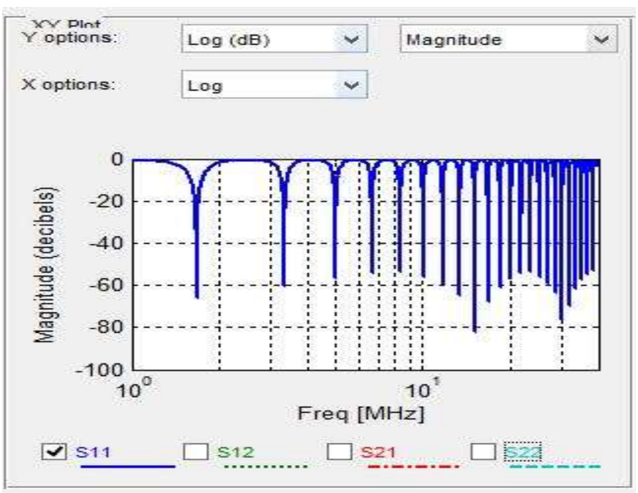

Figure-7 Magnitude Response of Logarithmic Scale at 40 MHz

4.4 Phase Response At 40 MHz

Phase response shows how the phase of a signal behaves with respect to frequency, when it is transmitted on a channel. Frequency is kept as parameter of horizontal x-axis whereas phase is kept as a parameter of vertical y-axis. For the phase response of a signal, values on the x-axis are linearly related and the phase is measured in radians on y-axis. Scale of frequency is given in MHz whereas phase is given in radians. Fig. 8 shows the phase response of a signal transmitted on the channel at 30MHz. S11 is the scattering parameter which is also called as reflection coefficient and is checked during simulations. In Fig. 8 it is shown that the phase response of a 40 MHz signal also remains linear when it is transmitted on the PLC channel. It can be said that the phase of signal is not too much affected on PLC channel at 40MHz because the phase of the signal almost remains linear. So it can be evaluated that the phase response of signals at 30MHz and 40 MHz remain same and it is not much affected by PLC channel.

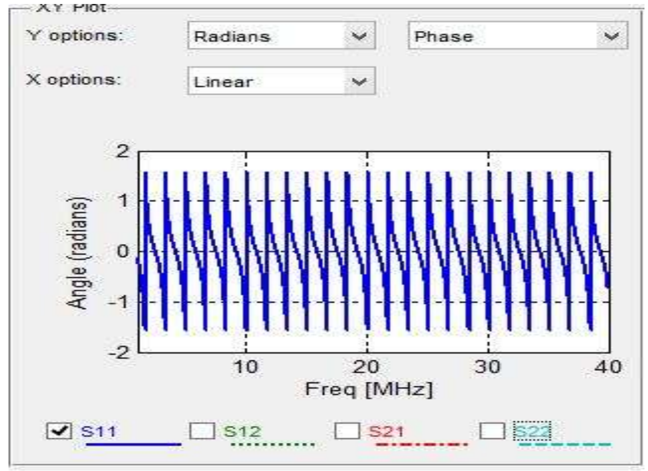

Figure-8 Phase Response at 40 MHz

5. CONCLUSIONS

In this research, PLC channel has been modelled as a two-wire transmission line channel. With the help of it, behaviour of the transmitted signals can be analysed in terms of voltage and current. It has been shown that the phase and magnitude of the transmitted signals depend on frequency and distance. It has also been stated that as frequency and distance increase more, the signals are more attenuated and distorted. So, it can be concluded that magnitude and phase response of the transmitted signals are functions of frequency and distance. Two parameters i.e. characteristic impedance and propagation constant have also been derived, which also contributes to the phase response and magnitude response of transmitted signal. By using echo-based model, the transfer function of PLC channel has been modelled, from which it can be observed that PLC channel contains multipath environment. After that in order to further strengthen the mathematical modelling concept, some simulations have been performed on MATLAB. Two different types of plots including magnitude response and phase response at 30MHz and 40MHz have also been illustrated. These simulation results showed that signals having higher frequency (i.e. 40 MHz) in comparison to the lower frequency (i.e. 30 MHz) are more attenuated in magnitude, however phase response of both the signals somehow remains linear.

6. FUTURE RECOMMENDATIONS

The PLC is envisioned as a platform for various Smart Grid (SG) applications [14], in which applications like automatic meter reading from remote distance and remote controlling of load can be used and it is also considered for high-data transfer rate. The management of the SG is based on command and control services that require robust, low-data-rate communications [15]. Therefore, advance receiver design techniques from wireless or wired communication should be adapted given the constraints of PLC and channel capacity bound may also be investigated. PLC can be used to enable vehicular communications and networking. The research is also going on in order to incorporate PLC technology in electric vehicles for making less use of electric wires in vehicular systems [16]. PLC can efficiently be used in application of home networking scenarios [17].

REFERENCES

[1] Tang L.T., So P.L., Gunawan E., ChenS., LieT. T., Guan Y.L., “Characterization of In-House Power Distribution Lines for High Speed Data Transmission”, Conference of Fifth International Power Engineering Conference (IPEC2001), Vol. 1, pp.7-12, Singapore, May 2001.

[2] Tanaka M., “High frequency noise power spectrum, impedance and transmission loss of power line in Japan on intra-building power line communications”, journal of IEEE Transactions on Consumer Electronics, Volume34, No.2, pp.321–326 , 2002.

[3] H. Philipps, “Development of a Statistical Model for Power line Communication Channels”, Proceeding 4th International Symposium on Power Line Communications and its Applications, Ireland, April 2000.

[4] Bo Tan and Tompson John, "Powerline Communications Channel Modelling Methodology Based on Statistical Features.", arXiv preprint arXiv:1203.3879, 2012.

[5] Ferriara HC, Grove HM, Hooei jen O and Wink AJ Hank, “Power Line Communication (Overview)”, Conference of IEEE AFRICON 4th, Volume 2, pp.558-563, September 1996

[6] Mannan Abdul, Saxena D.K. and Banday Mahroosh, “A Study on Power Line Communication”, Journal of International Journal of Scientific and Research Publications, Volume 4, No. 7, July 2014

[7] Andrea dou Nikoleta and Tonello M. Andrea,“On the Mitigation of Impulsive Noise in Power-Line Communications With LT Codes”, Journal of IEEE transactions on power delivery, Volume 28, No. 3, pp.1483-1490, July 2013

[8] Meng H, Chen S, Guan Y.L, “A Transmission line Model for High Frequency Power line Communication Channel”, International conference on Power System Technology Proceedings IEEE, Volume 2, pp.1290-1295, October 2002

[9] Thomas Mini. S., Chandna Kumar, Vinayand Arora Seema,“Load Modelling of Broadband Power line Communication Channel (BPLC) Network”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, Volume 2, Special Issue 1, December 2013

[10] Meng H, Chen S, Guan Y.L, “Modelling of Transfer Characteristic of Broadband Power Line Communication Channel”, Journal of Power Delivery, IEEE Transactions on Volume 19, No. 3, pp. 1057-1064,July 2004

[11] Sartenear T., Delogne P., “Power Cables Modelling for Broadband Communications”, Proceeding International Symposium Power Line Communication and Its Applications, Ireland , April 2001

[12] Banwell T.C.,Galli S., “A New Approach to the Modelling of the Transfer Functions of Power Line Channel”, proceeding International Symposium on Power Line Communications and Its Applications, Ireland, April 2001

[13] Chen Hongyu, Shi Rui, Cheng Chung-Kuan, "Surfliner: a distortionless electrical signaling scheme for speed of light on-chip communications" published in Computer Design: VLSI in Computers and Processors, 2005. ICCD 2005. Proceedings. 2005 IEEE International Conference on, vol., no., pp.497-502, 2-5 Oct. 2005

[14] M. Nassar, Lin Jing, Y. Mortazavi, A. Dabak, Kim Han ll, B.L Evans, “Local Utility Powerline Communications in the 3-500kHz Band: Channel impairments, Noise and Standards”, Journal of Signal Processing Magazine, IEEE, Volume 29, No. 5, pp. 116-127, 2012

[15] Tonello M. Andrea, Versolatto Fabio, and Gritto Mauro, “Multi-technology (I-UWB and OFDM) Coexistent Communications on the Power Delivery Network”, Journal of IEEE transactions on power delivery, Volume 28, No. 4, pp. 2039-2047, October 2013

[16] Nouvel Fabiennie, Tanguy Philippe, “In Vehicle Communication Networks: A Power line communication Study and Demonstrator for Infotainment Applications”, Conference of ICSNC, the Ninth International Conference on Systems and Networks Communications in France, 2014

[17] Antoniali Massimo and Tonello M.Andrea, Senior Member, IEE, “Measurement and Characterization of Load Impedances in Home Power Line Grids”, Journal of IEEE transactions on instrumentation and measurement Volume 63, No.3, pp.548–556, October 2013