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Characterization and Modeling of Low Voltage Distribution Networks for High Speed Data Transmission

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ABSTRACT

Communication over electric power distribution lines (PLC) has been in existence for a long period of time. The current systems utilizes narrow bandwidth which limits the communication speed. For high speed data communication, broad bandwidth is required. This paper analyses the characteristics of indoor and outdoor distribution networks in Nigeria for high speed data transmission. From measurement results, signal transmission models for indoor and outdoor distribution networks in the frequency band of 1-10 MHz were developed. From the results obtained, the networks exhibits frequency selectivity. Third order polynomial models and low order finite impulse response models are sufficient to describe the power line channels.

Keywords: *Power line communication, characterization, modeling*

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I INTRODUCTION

Although power line communication is an old technology, its current applications are limited to applications that require narrow bandwidth such as automatic meter reading, feeder switching, load control etc. For such applications that operates with low bit rate, standards have well been developed which varies from one country to another. In Europe, the operations of power line communication is limited to frequency band of 3-150 kHz while in Japan, Canada and USA up to 500 kHz is allowed. For applications that require high speed data transmission such as internet communication, broader bandwidth in the range MHz is required. This necessitates investigation into characteristics of distribution networks around the globe in the frequency range of MHz. Many researchers have presented works on the measurements and modeling of power networks characteristics around the world.

The time and location variation of power line communication channel parameters made it difficult to estimate signal transmission characteristics by direct calculation (Jingbo *et al*., 2005). This necessitates practical measurements. Selandar (1999) measured signal attenuation and noise of low voltage distribution networks in Sweden in the frequency range of 1-16MHz.The attenuation was found to increase with frequency and above 10MHz is hard to distinguish the received signal from the background noise. Tang *et al.* (2003) measured signal attenuation, load impedance, and noise of indoor power lines in Singapore in the frequency range of of 1-10MHz.They found that signal attenuation and noise expected amplitude decreases with frequency while load impedance increases with frequency. From the measurement results they developed models for the transfer function and noise. Channel models for power networks are very important for theoretical analysis and power line communication system design (Jingbo, 2005). Meng *et al.* (2004) presented a transfer characteristics model for broadband power line communication channel. They approximated power line as transmission line and the characteristic impedance and propagation constants were derived based on lumped –element circuit model. The model was verified through practical measurements on actual power line. Sabolic *et al.* (2005) developed a signal propagation modeling in power-line communication networks based on frequency-domain analysis. In his model, the transfer function is calculated from impedances that can be calculated on network ports. Anatory *et al.* (2007) developed channel model for broadband power line communication. The model simulation results is comparable to ATP-EMTP results. In this paper, we measured signal attenuation of indoor and outdoor distribution networks in Nigeria in the frequency band of 1-10 MHz. From the measurement results, transfer function models were developed.

The rest of the paper is divided as follows. Section II presents field measurements of signal attenuation of out-door and in-door low voltage distribution networks. In Section III power line channel models are developed. Section IV, presents derived channel for both in-door and out-doors power distribution networks. In Section, V, the results of the signal transmission and channel models derived are discussed extensively. In section VI, we presents the conclusion.

II FIELD MEASUREMENTS OF SIGNAL TRANSMISSION ATTENUATION

Although the distribution network topology and electric wires are known, it is not adequate to rely on signal attenuation obtained by direct calculation to characterize power line channels since detail information on the load is not available. Hence, there is the need for field measurement. In this study, Signal transmission measurements in the frequency band of 1-10 MHz were carried out in two categories as follows:

- In building signal transmission attenuation measurement
- Out-door signal transmission attenuation measurement

A MEASUREMENT SETUP

The measurements have been carried out with a two channel oscilloscope of 20 MHz bandwidth and function generator of 150 MHz bandwidth. In order to protect the sensitive equipments from damaging by the 50Hz main power, passive high pass filters have been used. Schematic diagram of the measurement setup, high pass filter circuit and coupling unit equivalent circuit are shown in figures 1, 2 and 3 respectively. Figure 4 is the frequency response of the high pass filter.

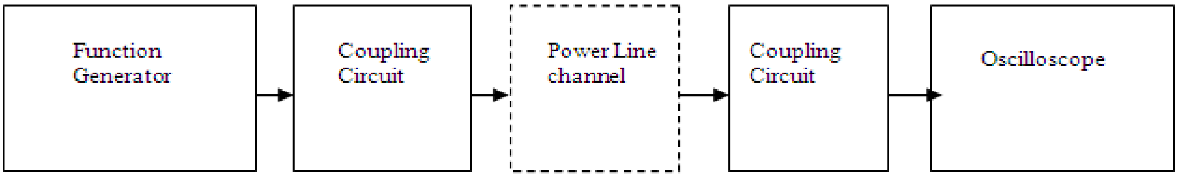

Figure 1: Schematic diagram of measurement set-up

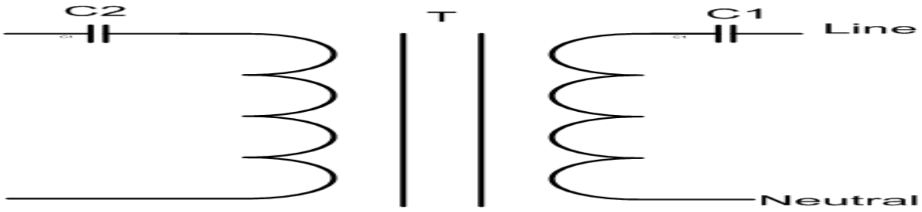

Figure 2: High Pass Filter Circuit

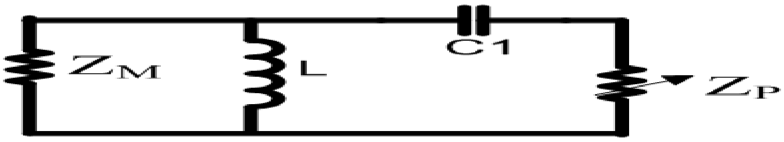

Figure 3: Coupling unit equivalent circuit

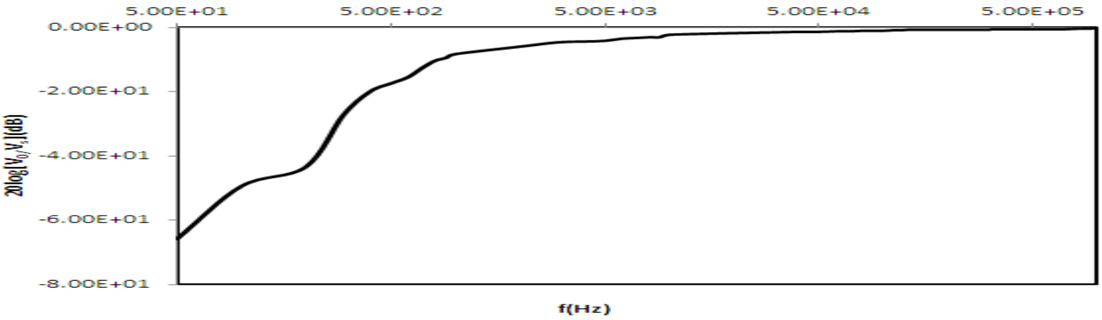

Figure 4: High Pass Filter Frequency Response

The capacitor C_1 and self-inductance of the transformer, T, form a series resonance circuit, a high pass filter to remove 50Hz frequency signal, its harmonics and all other spectral components with low frequencies. C_2 is used to prevent the shorting of dc offset of the transmitter and is not required when using the filter on the receiver side. The cut-off frequency of the high pass filter is 3 kHz.

B IN-BUILDING SIGNAL ATTENUATION MEASUREMENT

In-building signal strength measurement is important for the design of home automation and internet access in homes and offices via power lines. Intensive Measurements in the frequency range of 1-10MHz were carried out in thirty homes in Bauchi metropolitan of north eastern Nigeria over a period of six months. In these experiments a function generator was used to produce the high frequency signal which is coupled into the power line through a high pass filter. At a distant location, the signal was coupled out through a high pass filter and measured with an oscilloscope. The access points were reached with the help of connection wires whose effects and that of the filters were considered. To obtain the signal attenuation between the two access points, the received signals were normalized to the transmitted signal level. The means of the signal attenuation and their standard deviations were determined and plotted as functions of frequency.

C OUT-DOOR SIGNAL ATTENUATION MEASUREMENT

Outdoor signal attenuation measurement is important for the purpose of applications such as remote meter reading, remote control of home appliances, local area networking and internet access via power lines. Here also measurements were done in the frequency range of 1-10 MHz for high bit rate applications. To determine the outdoor signal attenuation, extensive measurements of signal strength were carried out in low voltage distribution networks in Bauchi, north-eastern Nigeria over a period of six months. The distribution network of the area is over head 415V/240V three phase four wire low voltage network. High frequency signals were coupled into the power line through a high pass filter at the transformer and received at various remote locations in the network. The means of the signal attenuation and their standard deviations in the frequency range of 1-10 MHz were determined and plotted as functions of frequency. The results obtained for indoor and outdoor measurements are shown in figures 5 and 6. From the results, the attenuation is frequency selective and agrees with the theoretical results for high load impedance networks obtained by Tijjani and Aliyu (2014) and measurement results presented by Dostert (1998), Tang et al (2003) and Selandar (1999). The in-door and out door signal attenuations varies between -28.79 to -7.23 dB and -36.1 to -9.51 dB respectively.

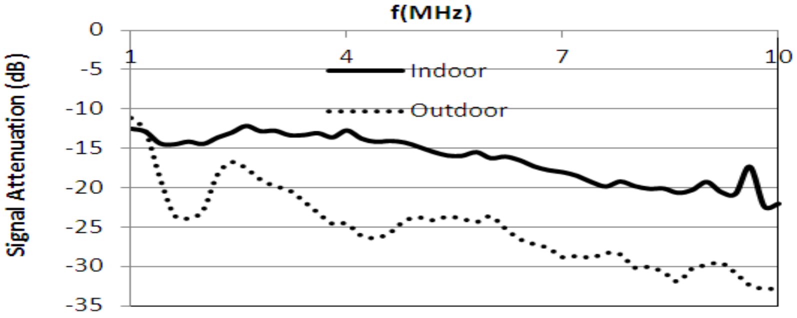

Figure 5: Indoor and outdoor signal average signal attenuation in the frequency band of 1-10 MHz

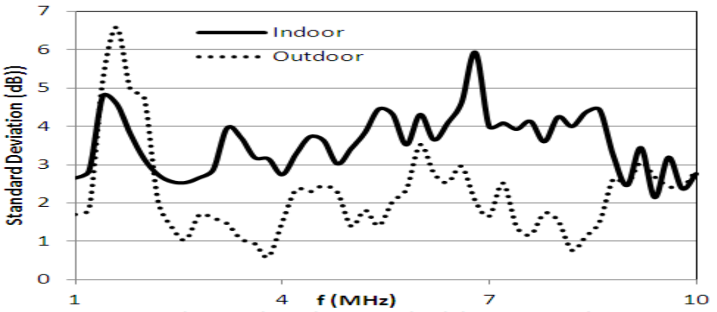

Figure 6: Indoor and outdoor standard deviation in the frequency band of 1-10 MHz

III POWER LINE COMMUNICATION CHANNEL MODELS

Efficient communication systems are generally tailored to the properties of the communication channels. Channel models of power networks are very important for the design of power line communication system. To get power line communication channel model a polynomial function can be used to fit a measured data (Jingbo et al,2005). Linear model cannot describe the detail of the channel and high order polynomial is often used. Also from the topology and measurement results, power networks can be considered as linear systems. Hence as linear systems power line communication channels can be described by its discrete impulse response. In order to developed power line communication channel models for indoor and outdoor distribution networks in Nigeria for high speed data transmission, field measurement results obtained were used.

A PROBABILISTIC MODELS

Probabilistic models are models that takes into account of random error. If probabilistic model involve higher order terms or more than one independent variable, such models are called multiple regression models. The general form of these models is;

$$Y = A_0 + A_1 X_1 + A_2 X_2 + \dots\dots\dots\dots A_i X_i + \varepsilon \qquad \text{.... (1)}$$

The dependent variable is written as a function of i independent variables, $X_1, X_{2, \dots\dots\dots\dots} X_i$. The random error term is added to allow for deviation between the deterministic part of the model $A_0+A_1X_1+A_2X_2+\dots\dots\dots A_iX_i$ and the value of the dependent variable ,Y. In order to develop probabilistic model the following steps are considered.

1) First, the form of the model was hypothesised. This involves the choice of the independent variables to be included in the model
2) Next, the unknown parameters $A_1, A_1, A_2 \dots A_i$ were estimated based on least square fit
3) Then, the adequacy of the models were checked
4) Finally, the fitted models were used to predict a particular value of transfer function

The least-square approach minimizes the sum of the squares of the deviation of the data from the model. That is, for the estimated model

$$\hat{Y} = \hat{A}_0 + \hat{A}_1 X_1 + \hat{A}_2 X_2 + \dots\dots\dots\dots \hat{A}_i X_i \qquad \text{.... (2)}$$

We minimizes

$$SSE = \sum_{i=1}^{n} (Y_i - \hat{Y})^2 \qquad \text{....(3)}$$

(Scheaffer and McClave, 1982).

B FINITE IMPULSE RESPONSE (FIR) MODEL

From the topology and measurement results, power networks can be considered as linear systems. Hence as linear systems power line communication channels can be described by its frequency response or discrete impulse response. The channel model can be realized in hardware using a transversal (taped delay) structure shown in figure 7.

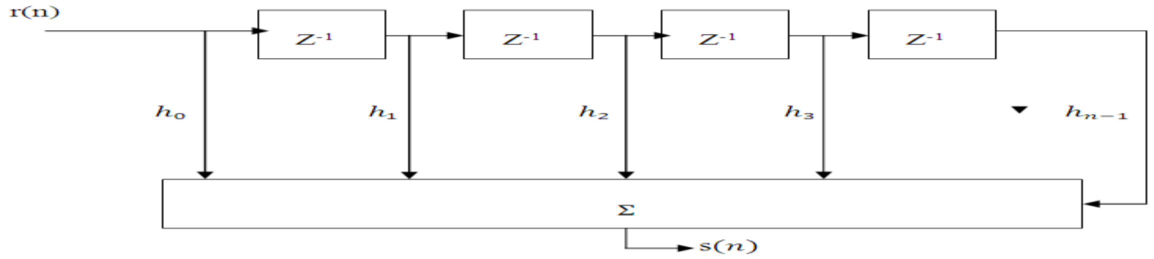

Figure 7: Transversal filter structure.

The discrete finite impulse response of the channel model **h** = $[h_0, h_1, h_2 \dots\dots. h_{M-1}]$ are obtained by minimization of mean square error. The mean squared error is defined as:

$$E = \sum_{k=0}^{N-1} \left| H(z) - H_d(z) \right|^2 \qquad \text{. . . (4)}$$

Where H(z) = model transfer function of the channel
$H_d(z)$ = desired transfer function of the channel

$$H(z)=\sum_{n=0}^{M-1} h_n e^{-j\omega n} \qquad \text{….(5)}$$

$$E=\sum_{k=0}^{N-1}\left|\sum_{n=0}^{M-1} h_n e^{-j\omega n}-H_d(z)\right|^2 \qquad \text{…(6)}$$

In terms of frequency samples, E can be written as

$$E=\sum_{k=0}^{N-1}\left|\sum_{n=0}^{M-1} h_n e^{-j2\pi\frac{k}{N}n}-\widetilde{H}_d(k)\right|^2 \qquad \text{….(7)}$$

k= 0, 1, ………………,N-1

Using minimization of mean squared error, we seek for the values of **h** = [h_0, h_1, h_2……..h_{M-1}] that minimizes the expression

$$E=\sum_{k=0}^{N-1}\left|\sum_{n=0}^{M-1} h_n e^{-j2\pi\frac{k}{N}n}-\widetilde{H}_d(k)\right|^2 \qquad \text{….(8)}$$

The impulse response h_i that minimize E satisfy the equation

$$\frac{\partial E}{\partial h_i}=0 \text{ , where i = 0, 1, 2…..M} \qquad \text{... (9)}$$

$$\frac{\partial E}{\partial h_i}=\frac{\partial}{\partial h_i}\sum_{k=0}^{N-1}\{\left(\sum_{n=0}^{M-1} h_n e^{-j(2\pi nk/N)}-\widetilde{H}_d(k)\right)\left(\sum_{in=0}^{M-1}\overline{h}_n e^{j(2\pi inkN)}-\overline{\widetilde{H}}_d(k)\right)\} \qquad \text{.(10)}$$

$h_i=\overline{h}_i$, since h is real

$$\frac{\partial E}{\partial h_i}=\frac{\partial}{\partial h_i}\sum_{k=0}^{N-1}\{\left(\sum_{n=0}^{M-1} h_n e^{-j(2\pi nk/N)}-\widetilde{H}_d(k)\right)\left(\sum_{in=0}^{M-1} h_n e^{j(2\pi inkN)}-\overline{\widetilde{H}}_d(k)\right)\} \qquad \text{…(11)}$$

Differentiating E with respect to h_i and setting the derivative equal to zero results in the following linear equation:

Ch=B …. (12)

Where

$$C(x,y)=2\sum_{k=0}^{N-1}\cos(x-y)\frac{2\pi k}{N} \qquad \text{…. (13)}$$

$$B(x)=\sum_{k=0}^{N-1}[2\cos\frac{(x-1)2\pi k}{N}.\mathrm{Re}(\widetilde{H}(k))-2\sin\frac{(x-1)2\pi k}{N}.\mathrm{Im}(\widetilde{H}(K))] \qquad \text{….(14)}$$

C is M x M matrix, B is M x 1 matrix , x, y =1,2………M (Jingbo et al,2005 and Oppenheim and Schafer,1989). The corresponding frequency parameter can be obtained by taking Fast Fourier Transform of **h**.

III DERIVED CHANNEL MODELS

Equations (15) and (16) are the fitted nonlinear models of the average in-door and out door signal attenuations respectively.

$$20\log|H(f)|=-16.4837+2.9599f-0.7181f^2+37.73*10^{-8}f^3 \qquad \text{. . . (15)}$$

$$20\log|H(f)|=-11.4185-4.7621f+0.5738f^2-31.4964*10^{-3}f^3 \qquad \text{... (16)}$$

The fitted nonlinear models for the typical in-door and outdoor signal attenuations are given in equations (17) and (18) .

$$20\log|H(f)| = -12.8825 - 1.3886f + 0.1753f^2 - 10.2907*10^{-3}f^3 \quad ..\ (17)$$

.

$$20\log|H(f)| = -21`.0946 + 1.1077f - 45.9688*10^{-2}f^2 + 27.1253*10^{-3}f^3 \quad ..\ (18)$$

The measured and predicted average attenuations are shown in the figures 8-11. Figures 12 and 13 shows relative errors between FIR models. These results show that third order polynomials and lower order FIR models are sufficient to characterize the channels.

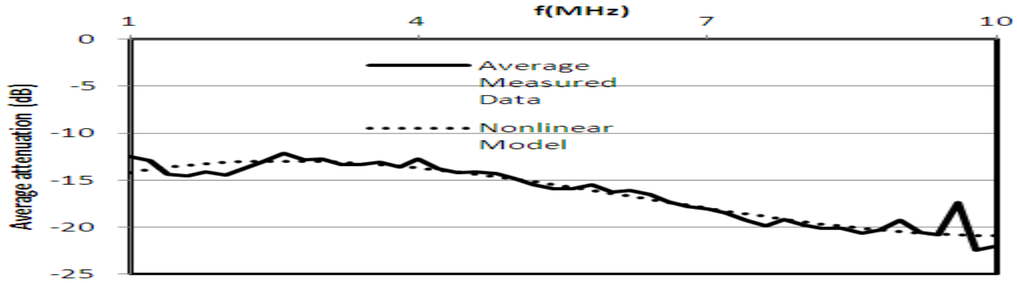

Figure 8: In-door average signal attenuation and its model in the frequency range of 1-10 MHz

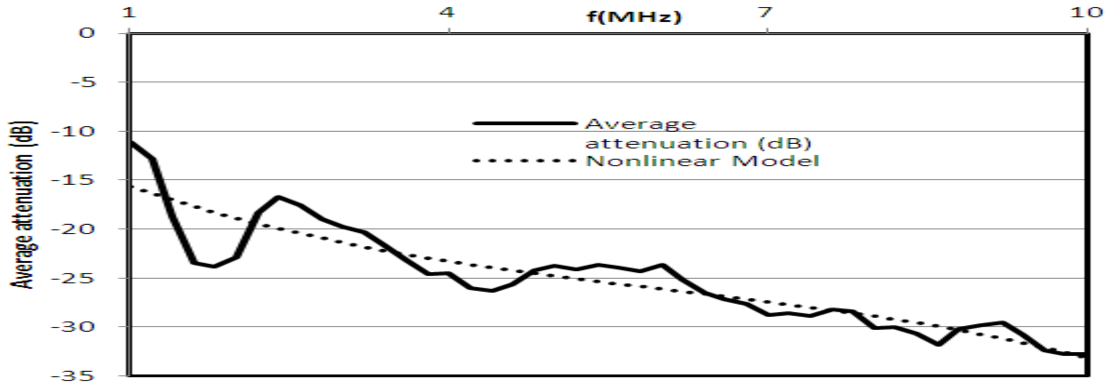

Figure 9: Out-door average signal attenuation and its model in the frequency range of 1-10 MHz

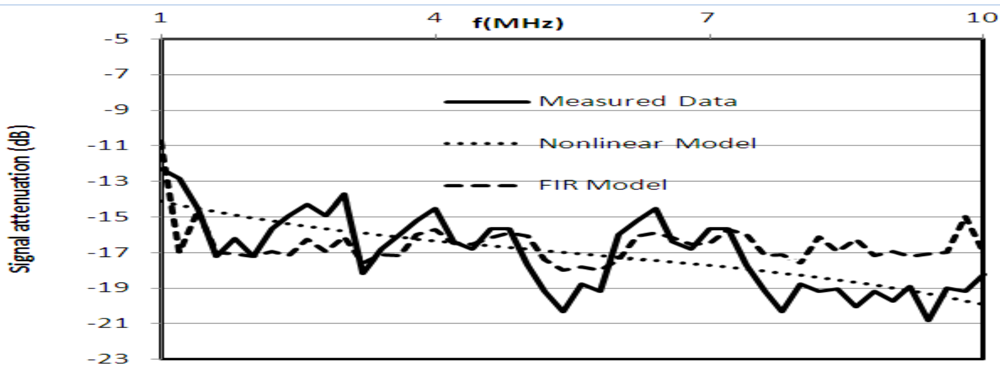

Figure 10: In-door signal attenuation and its model in the frequency range of 1-10 MHz

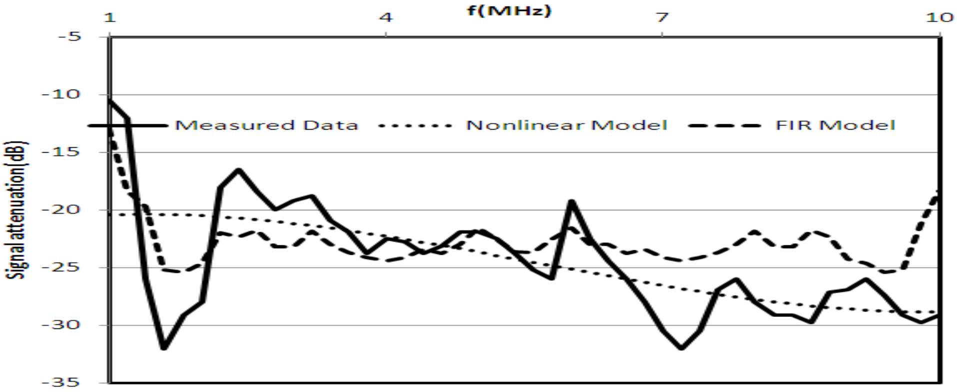

Figure 11: Out-door signal attenuation and its models in the frequency range of 1-10 MHz

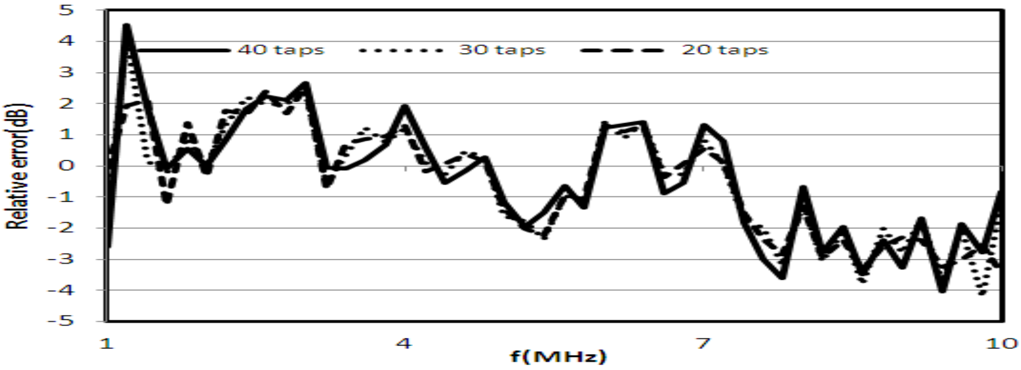

Figure 12: Relative error between measured attenuation and FIR Models for indoor channels

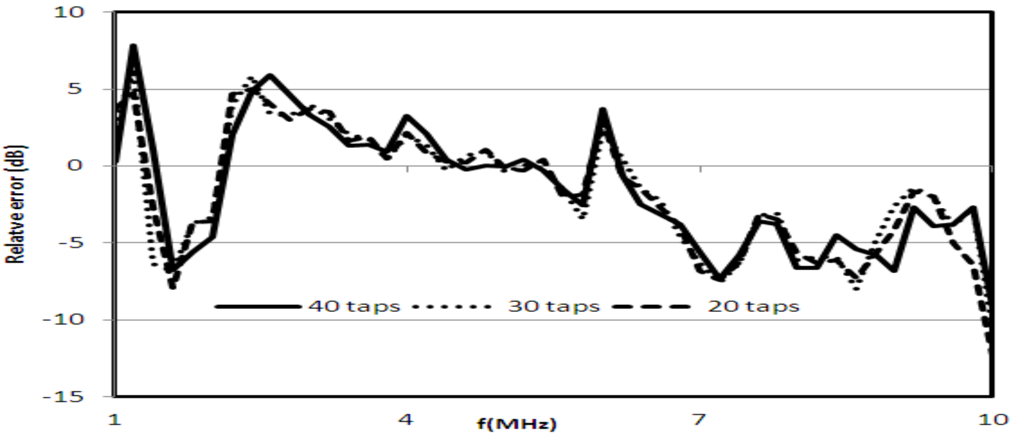

Figure 13: Relative error between measured attenuation and its FIR Models for outdoor channels

VI CONCLUSION

To design an efficient power line communication system over distribution networks, signal transmission characterization is essential. In this work signal transmission characterization of power line distribution networks is presented for high bit rate power line communication system. It was observed that the signal attenuation varies with frequency for both in-door and out-door distribution networks hence they are frequency selective. From the measured characteristics, we derived third order polynomial models and finite impulse response models for both in-door and out-door distribution networks in the frequency band of 1-10 MHz.

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