Performance Analysis of a Power Line Communication System with Multi-Carrier DS-CDMA

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Abstract— **Power line communication (PLC) system is evolving as a ubiquitous communication system for high speed broadband data communication. Multicarrier DS-CDMA (MC-DS-CDMA) technique is an attractive technique in achieving high data-rate transmission in wireless communication. In this paper, analytical approach is developed to combine the MC-DS-CDMA technology with the features and characteristics of a PLC system. To find the effectiveness of MC-DS-CDMA system in a power line channel, a system model is proposed for high speed data communication through a power line channel using the DS-CDMA with multicarrier orthogonal FDM (OFDM) technique. Analysis is carried out by considering the combined effect of power line impulsive noise, channel transfer function, effect of load impedances and the number of branches in a PLC network. Expressions of signal to interference and noise ratio and bit error rate (BER) at output of CDMA receiver are developed considering the above limitations.**

Index Terms— **Power Line Communication (PLC), Multi-carrier DS CDMA, OFDM, SINR. BER**

I. Introduction

A model of a power line communication system (PLC) will be proposed which will include different number of branches, different types of devices and loads. Analysis will be carried out for a power line communication link considering the transfer function of the power line with different number of branches, load impedances, line length and device characteristics. Considering Multi-Carrier DS-CDMA, analysis will be done to find the expression of the signal at the output of the power line at the receiving end along with the channel noise. The expression for signal to interference and noise ratio and the expression of bit error rate (BER) will be developed. The performance result will be evaluated in terms of output signal spectrum and BER performance for a given system parameters and power line parameters.

II. PLC System Model with MC-DS-CDMA

For this analysis, we have considered that, our system model will have the following PLC Channel model, PL noise model, Transmitter model and Receiver model.

A. PLC Channel Model

In this paper, the generalized channel model proposed in [1] for a power-line network with distributed branches as shown in figure 1 [1] is proposed. The branches are

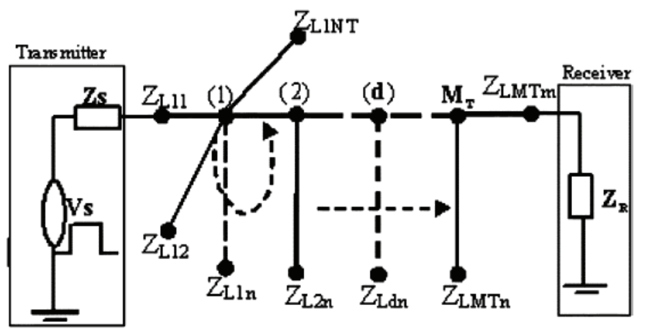

Figure 1. Power Line network with distributed branches

either concentrated at a given node or distributed in the link between the transmitting on and receiving end [1]. The transfer function of this network is given by Eq.(1).

$$H_{mM_T}(f) = \prod_{d=1}^{M_T} \sum_{M=1}^{L} \sum_{n=1}^{N_T} T_{Lmd}\, \alpha_{mnd}\, H_{mnd}(f) \quad (1)$$

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

$$P_{Lnd} = \begin{cases} \rho_s & d=n=1(source) \\ \rho_{Lnd} & otherwise \end{cases} \quad (3)$$

In Eq.(1), N_T is the total number of branches connected, say at node "1" and terminated in any arbitrary load. n, m, M, $H_{mnd}(f)$ and T_{Lmd} represent any branch number, any referenced (terminated) load, number of reflections(with total L number of reflections), transfer function between line n to a referenced load m at the referred load "d" and the transmission factor at the referenced load m at referred node "d" respectively. With these, the signal contribution factor $\dot{\alpha}_{mnd}$ is given by Eq.(2) where $\dot{\rho}_{nmd}$ is the reflection factor at node "d" between line "n" to the referenced load m, γ_{nd} is the propagation constant of line " n" that has line length l. All terminal reflection factors $P_{Lnd,}$ in general are given by Eq.(3) except at the source where $\dot{\rho}_{L11}= \dot{\rho}_s$ is the source reflection factor.

B. *Power Line Noise Model*

The power-Line channel suffers impulsive noise interference that is generated from connected electrical appliances. Middleton class A noise model is one of the appropriate models for impulsive noise environment [2]. Based on the model, the combination of impulsive plus background noise is a sequence of iid complex random variables with the probability density function of class A noise is given by,

$$P_z(z) = \sum_{m=0}^{\alpha} \frac{\alpha_m}{2\pi\sigma_{m^2}} \exp\left(-\frac{z^2}{2\sigma_{m^2}}\right) \quad (4)$$

Where, m is the number of impulsive noise source and is characterized by poisson distribution with mean parameter "A" called the impulsive index (which is the product of the average rate of impulsive noise and the mean duration of typical impulse)

$$\alpha_m = e^{-A}\frac{A^m}{\angle m} \quad (5)$$

$$\sigma_m^2 = \left(\sigma_g^2 + \sigma_i^2\right)\frac{\left(\frac{m}{A}\right)+\Gamma}{1+\Gamma} . \Gamma = \frac{\sigma_g^2}{\sigma_i^2} \quad (6)$$

Where, σ_g^2 and σ_i^2 are the power of background noise and impulsive noise respectively. For small A, we get highly structured impulsive noise where as for large values of A, the noise PDF becomes Gaussian. The parameter Γ (GIR- Gauss Impulsive power ratio) is called background – to – Impulsive noise ratio. Eq. (4) shows that the PDF of noise is a weighted sum of Gaussian PDF's with zero mean, therefore has a mean of μ_z=0 and a variance of

$$\sigma_z^2 = E\{z^2\} = \sum_{m=0}^{\alpha} \alpha_m \cdot \frac{1}{2\pi\sigma_m^2}\int z^2 . \exp\left(-\frac{z^2}{2\sigma_m^2}\right) \quad (7)$$

$$= \frac{e^{-A}\sigma_g^2}{\Gamma}\sum_{m=0}^{1}\frac{A^m}{\angle m}\left(\frac{m}{A}+\Gamma\right) = \left(\sigma_g^2+\sigma_i^2\right) \quad (8)$$

C. *Functional block diagram of PLC system with MC-DS - CDMA*

The functional block diagram of a power line communication system with MC-DS-CDMA is shown in Figure 2. It includes S/P converter, transmitter, power line channel, receiver and P/S converter.

A. *Transmitter Model*

Block diagram of a DS-CDMA with multicarrier OFDM transmitter is shown in Figure 3. In the transmitter, the high-speed data are converted into parallel data stream and are OFDM modulated.

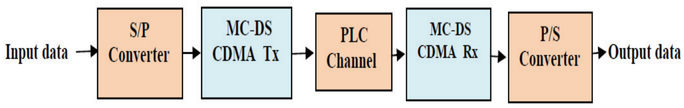

Figure 2. Functional block diagram of PLC System with MC-DS CDMA

The output of OFDM modulator is fed to PLC channel after RF amplification.

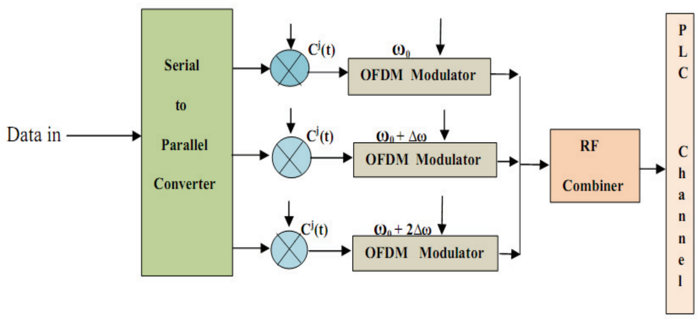

Figure 3. Block diagram of MC- DS-CDMA transmitter for power line communication

B. *Receiver Model*

Block diagram of MC-DS-CDMA receiver is shown in Figure 4. The received signal is first amplified by RF

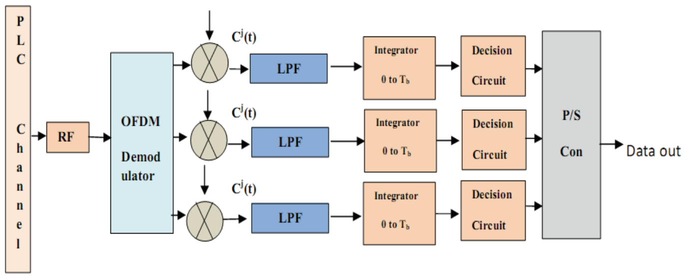

Figure 4. Block diagram of MC- DS-CDMA receiver with power line channel

amplification and passed to a coherent OFDM demodulator. Output of OFDM demodulator is passed to the decoder blocks. Decoding is carried out using a locally generated code sequence. To be able to perform the dispreading operation, the receiver must not only know the code sequence used to spread the signal, but the codes of the received signal and the locally generated code must also be synchronized. The decoded outputs are passed through integrator and passed to data decision circuit. The output of the decision circuit is then converted to serial data.

III. SYSTEM ANALYSIS

A. *Transmitted Signal*

Let us consider an MC-DS-CDMA system, the block diagram of MC-DS-CDMA is shown in the Figure 2. Let for any period of time, there are "J" numbers of users and "j" is the reference user. Now to have a system model, let us make following assumptions:

a. All the users are active at any time
b. All the user's transmitter power levels are equal
c. The bit rate is much larger than chip rate

Now, let us consider the following terms for this system :

J = Total no of user
P = Chip power of each user
N_c= Number of sub-carriers
N = Number of chip of the code for each sub- carrier channel
L = Code length of each user
C^j = Code of j-th user
R_b= Bit-rate
$m_j(t)$= Input data stream of the j-th user
b_n^j= n-th bit of $m_j(t)$

Thus, $\quad m_j(t) = \sum_{n=-\infty}^{\infty} b_n{}^j \quad$; where $b = \pm 1$

Now, the input data of the j-th user are converted into *Nc* parallel data streams and each of the parallel data is coded by the code of the j-th user. Thus each data bit is spreaded in time domain and then modulated by the respective subcarrier. To write the general expression of the subcarriers, let us consider the following:

ω_0 = Frequency of the reference channel
$\Delta\omega$ = Frequency spacing between two subcarrier channel

So, the general expression of a subcarrier is :

$$\sqrt{2P}\cos(\omega_0 t + k\Delta\omega) \tag{9}$$

Thus, the expression of the transmitted signal of the j-th user is as follows :

$$S_T(t) = \sum_{k=1}^{Nc}\left\{\sqrt{2P}\, b_{n,k}^j \left(\sum_{i=1}^{G_P} C_i^j \times P(t - it_c)\right)\cos(\omega_0 t + k\Delta\omega)\right\} \tag{10}$$

Here,

$b_{n,k}^j$ = n-th bit of the j-th user, which is being modulated by the k-th subchannel.

C_i^j = i-th chip of the j-th user's code.

B. Receiver Output

While reception, the receiver of the j-th user receives signals transmitted by all the J number of users [3],[4],[5]. Thus, the expression of the received signal is :

$$r(t)=\sum_{j=1}^{J}[\ \sqrt{2P}\sum_{k=1}^{Nc}\left\{b_{n,k}^j\left(\sum_{i=1}^{Gp}C_i^j * P(t-it_c)\cos(\omega_0 t+k\Delta\omega t)\right)\right\}\otimes h_{ch}(t)\ \}+\sum_{k=1}^{N_c}n(t)\ ] \tag{11}$$

where, $h_{ch}(t)$ is the impulse response of the PLC channel, $\otimes$ denotes convolution and $n(t)$ is the channel noise.

The signal while propagating through power line channel, suffers frequency-selective multipath fading. To account the fading, consider that α be the instantaneous amplitude fading.

$$r(t)=\sum_{j=1}^{J}[\alpha\sqrt{2P}\sum_{k=1}^{Nc}\left\{b_{n,k}^j\left(\sum_{i=1}^{Gp}C_i^j * g(t-it_c)\cos(\omega_0 t+k\Delta\omega t)\right)\right\}]+\sum_{k=1}^{N_c}n(t) \tag{12}$$

Where,

$$g(t) = P(t)\otimes h_{ch}(t)$$
$$G(f)=P(f).\,H_{ch}(f)$$
$$G(f_k)=P(f_k).H(f_k)$$

This signal is then coherently demodulated by the respective carriers and the output $y_{(t)}$ can be represented as:

$$y(t)=\sum_{j=1}^{J}\alpha\sqrt{2P}\sum_{k=1}^{Nc}\left\{b_{n,k}^j\sum_{i=1}^{Gp}C_i^j * g(t-it_c)\cos(\omega_0 t+k\Delta\omega t)*\cos(\omega_0 t+k\Delta\omega t)\right\}+\sum_{k=1}^{Nc}n(t)*\cos(\omega_0 t+k\Delta\omega t)$$
$$=\sum_{j=1}^{J}\alpha\sqrt{2P}\sum_{k=1}^{Nc}\left\{b_{n,k}^j\sum_{i=1}^{Gp}C_i^j * g(t-it_c)\cos^2(\omega_0 t+k\Delta\omega t)\right\}+\sum_{k=1}^{Nc}n(t)*\cos(\omega_0 t+k\Delta\omega t)$$
$$=\sum_{j=1}^{J}\alpha\sqrt{2P}\sum_{k=1}^{Nc}\left\{b_{n,k}^j\sum_{i=1}^{Gp}C_i^j * g(t-it_c).\tfrac{1}{2}(1+\cos(2\omega_0 t+2k\Delta\omega t))\right\}+\sum_{k=1}^{Nc}n(t)*\cos(\omega_0 t+k\Delta\omega t)$$
$$=\sum_{j=1}^{J}\alpha\sqrt{2P}\sum_{k=1}^{Nc}\left\{b_{n,k}^j\sum_{i=1}^{Gp}C_i^j * g(t-it_c)(1+\cos(2\omega_0 t+2k\Delta\omega t))\right\}+\sum_{k=1}^{Nc}n(t)*\cos(\omega_0 t+k\Delta\omega t)$$

It is then decoded and the output of the correlator is given by :

$$y(t)=\sum_{j=1}^{J}\alpha\sqrt{2P}\sum_{k=1}^{Nc}\left\{b_{n,k}^j\left(\sum_{i=1}^{Gp}C_i^j * g(t-it_c)*\sum_{i=1}^{Gp}C_i^1 P(t-it_c)\right)(1+\cos(2\omega_0 t+2k\Delta\omega t))\right\}$$
$$+\sum_{k=1}^{Nc}n(t)\sum_{i=1}^{Gp}C_i^j P(t-it_c)\cos(\omega_0 t+k\Delta\omega t)$$
$$y(t)=\sum_{j=1}^{J}\alpha\sqrt{2P}\sum_{k=1}^{Nc}b_{n,k}^j\left\{\sum_{i=1}^{Gp}C_i^j g(t-it_c)*\sum_{i=1}^{Gp}C_j^1 P(t-it_c)\right\}$$
$$+\sum_{j=1}^{J}\alpha\sqrt{2P}\sum_{k=1}^{Nc}b_{n,k}^j\left\{\sum_{i=1}^{Gp}C_i^j g(t-it_c)*\sum_{i=1}^{Gp}C_i^1 P(t-it_c)*\cos(2\omega_0 t+2k\Delta\omega t)\right\}$$
$$+\sum_{k=1}^{Nc}n(t)\sum_{i=1}^{Gp}C_i^j P(t-it_c)\cos(\omega_0 t+k\Delta\omega t)$$

After passing through low pass filter (LPF), the output of the LPF is given by :

$$y_0(t)=\alpha\sqrt{2P}\sum_{k=1}^{Nc}\left[b_{n,k}^j\sum_{i=1}^{Gp}C_i^1 g(t-it_c)*\sum_{i=1}^{Gp}C_i^1 P(t-it_c)\right]$$
$$+\sum_{j=2}^{J}\alpha\sqrt{2P}\sum_{k=1}^{Nc}\left[b_{n,k}^j\left\{\sum_{i=1}^{Gp}C_i^1 g(t-it_c)*\sum_{i=1}^{Gp}C_i^j P(t-it_c)\right\}\right]$$
$$+\sum_{k=1}^{Nc}n(t)\sum_{i=1}^{Gp}C_i^j P(t-it_c)\cos(\omega_0 t+k\Delta\omega t)$$
$$y_0(t)=\alpha\sqrt{2P}\sum_{k=1}^{Nc}\left[b_{n,k}^j\sum C_i^1 g(t-it_c)*\sum C_i^1 P(t-it_c)\right]$$
$$+\sum_{j=2}^{J}\alpha\sqrt{2P}\sum_{k=1}^{Nc}\left[b_{n,k}^j\left\{\sum_{i=1}^{Gp}C_i^1 g(t-it_c)*\sum_{i=1}^{Gp}C_i^j P(t-it_c)\right\}\right]$$

[i ≠ j , j=2]

$$+\sum_{k=1}^{Nc}n(t)\sum_{i=1}^{Gp}C_i^j P(t-it_c)\cos(\omega_0 t+k\Delta\omega t)$$

Now, after integrating over 0 to T_b, we get the following,

$$y_0(t) = \alpha\sqrt{2P}\sum_{k=1}^{Nc}\left[b_{n,k}^1 \frac{1}{T_b}\int_0^{T_b}\sum_{i=1}^{G_p} g(t-it_c) * \sum_{i=1}^{G_p} P(t-it_c)dt\right]$$

$$[C_i^1 \text{ x } C_i^1 = 1]$$

$$+\sum_{j=2}^{J}\alpha\sqrt{2P}\sum_{k=1}^{Nc}\left[b_{n,k}^j \frac{1}{T_b}\int_0^{T_b}\left\{\sum_{i=1}^{Gp} C_i^1 g(t-it_c) * \sum_{i=1}^{Gp} C_i^j P(t-it_c)dt\right\}\right]$$

$$+\frac{1}{T_b}\int_0^{T_b}\sum_{k=1}^{Nc} n(t)\sum_{i=1}^{Gp} C_i^j P(t-it_c)\cos(\omega_0 t + k\Delta\omega t)dt \quad (13)$$

$$y_0(t) = y_j(t) + y_{MAI} + n(t)$$

Here, $y_j(t)$ = Desired signal of j-th user

y_{MAI} = Multiple access interference

$n(t)$ = Noise

C. ***Desired Signal of Receiver***

$$y_j(t) = \alpha\sqrt{2P}\sum_{k=1}^{Nc}\left[b_{n,k}^1 \frac{1}{T_b}\int_0^{T_b}\sum_{i=1}^{G_p} g(t-it_c) * \sum_{i=1}^{G_p} P(t-it_c)dt\right]$$

$$= \alpha\sqrt{2P}\; N_c\,[\mu_{11}]$$

where,

$$\mu_{11} = \frac{1}{T_b}\int_0^{T_b}\sum_{i=1}^{G_p} g(t-it_c) * P(t-it_c)dt \quad \text{and}$$

$$N_c = \sum_{k=1}^{N_c} b_n^j$$

Thus, for the j-th user, the desired signal power, P_s is given as:

$$P_s = \alpha^2 2PN_c^2 \times (\mu_{11})^2$$

D. Multiple Access Interference (MAI)

The multiple access interference term of Eq (13) can be represented as :

$$y_{MAI}(t) = \sum_{j=2}^{J}\alpha\sqrt{2P}\sum_{k=1}^{Nc}\left[b_{n,k}^j \frac{1}{T_b}\int_0^{T_b}\left\{\sum_{i=1}^{Gp} C_i^1 g(t-it_c) * \sum_{i=1}^{Gp} C_i^j P(t-it_c)dt\right\}\right]$$

$$= (J-1)\alpha\sqrt{2P}\; N_c \times \frac{1}{G_p}\sum_{j=2}^{J}\mu_{ij}$$

where,

$$\mu_{ij} = \frac{1}{T_b}\int_0^{T_b}\left\{\sum_{i=1}^{Gp} C_i^1 g(t-it_c) * \sum_{i=1}^{Gp} C_i^j P(t-it_c)dt\right\} \quad \text{and}$$

$$N_c = \sum_{k=1}^{N_c} b_n^j$$

So the interference power is given as,

$$P_{MAI} = \frac{(J-1)\alpha^2 2PN_c^2 \times |\mu_{ij}|^2}{G_p}$$

E. Noise

The noise at the output of integrator is given by:

$$n(t) = \frac{1}{T_b}\int_0^{T_b}\sum_{k=1}^{Nc} n(t)\sum_{i=1}^{Gp} C_i^j P(t-it_c)\cos(\omega_0 t + k\Delta\omega t)dt$$

Here the noise is power line noise and the varience of the noise is given as,

$$\sigma_n^2 = \sigma_g^2 + \sigma_i^2$$

$$\sigma_n^2 = (\sigma_g^2 + \sigma_i^2)\frac{\left(\frac{m}{A}\right) + \Gamma}{1+\Gamma}$$

where,

$$\Gamma = \frac{\sigma_g^2}{\sigma_i^2} \;;\; N_m = \frac{\sigma_n^2}{R_b}$$

σ_g^2 and σ_i^2 represents the Gaussian and Impulsive noise varience respectively. Γ represent Gauss Impulsive power ratio and R_b is bit rate.

F. Signal to Interference and Noise Ratio (SINR)

The ratio of signal power to MAI and noise power can be expressed as:

$$SINR\ (\xi) = \frac{P_s}{P_{MAI} + \sigma_n^2}$$

$$= \frac{\alpha^2 2PN_c^2 \times (\mu_{11})^2}{(J-1)\alpha^2 2PN_c^2 \times |\mu_{ij}|^2 \times \frac{1}{G_p} + \sigma_n^2}$$

$$= \frac{\alpha^2 2 \times SNR \times N_c^2 \times (\mu_{11})^2}{(J-1)\alpha^2 2 \times SNR \times N_c^2 \times |\mu_{ij}|^2 \times \frac{1}{G_p} + BT \times \frac{N_m}{N_o}}$$

where $P = SNR$,

$$\sigma_n^2 = BT \times \frac{N_m}{N_0}$$

G. Bit Error Rate (BER) of the Receiver

The bit error rate of the coherent PSK receiver can be obtained as :

$$BER = 0.5 \times erfc\left(\sqrt{SINR / 2}\right)$$

where, erfc is the complementary error function.

IV. RESULTS AND DISCUSSION

Following the analysis, we evaluate the BER performance of a power line communication system and results are presented in Figure. 5 to Figure. 7. The values and list of parameters are shown in Table 1. We consider a given code sequence and found the signal at the output of receiver. From the sampled signal and interference values, μ_{11} and μ_{ij} are numerically evaluated for different code length, number of subcarriers and PLC system parameters.

A. BER Vs SNR for Different Line Impedances (Values of R,L and C varying)

The plots of BER of a MC-DS-CDMA power line communication system are shown in Figure 5 as a function of SNR with number of users as a parameter. The value of other parameters are G_p=64, number of subcarrier, N_c=4 and several values of RLC line components. It is noticed from the curves that the BER decreases with SNR upto certain value of SNR and then BER floor occurs. The BER floor occurs at a higher value of BER with increase in the number of simultaneous user.

Table 1 List of channel and system parameters

	Parameter	Value
Channel parameters	Resistance (R)	0.455 - 0.755ohm/m
	Inductance (L)	$0.443e^{-6}$ - $0.743\ e^{-6}$h/m
	Capacetance (C)	$61.734\ e^{-12} – 64.734\ e^{-12}$F/m
	Number of branch	04
	Branch length	10-25m, 15-30m, 23-38m, 20-35m
	Source impedance (Z_s)	70-85 ohm
System parameters	Number of subcarriers (N_c)	04
	Processing gain (G_p)	64
	SNR(dB)	30-70 dB
	User	2-32
	Δf	10 KHz
	Band Width	1-20 MHz
	Bit rate (R_b)	40 kbps

As noted from the figures, as the line impedance increases, the BER performance deteriorates and BER floor occurs at higher value of BER with increase in line impedance. For some values of line parameters, BER floor occurs at or above 10^{-2}

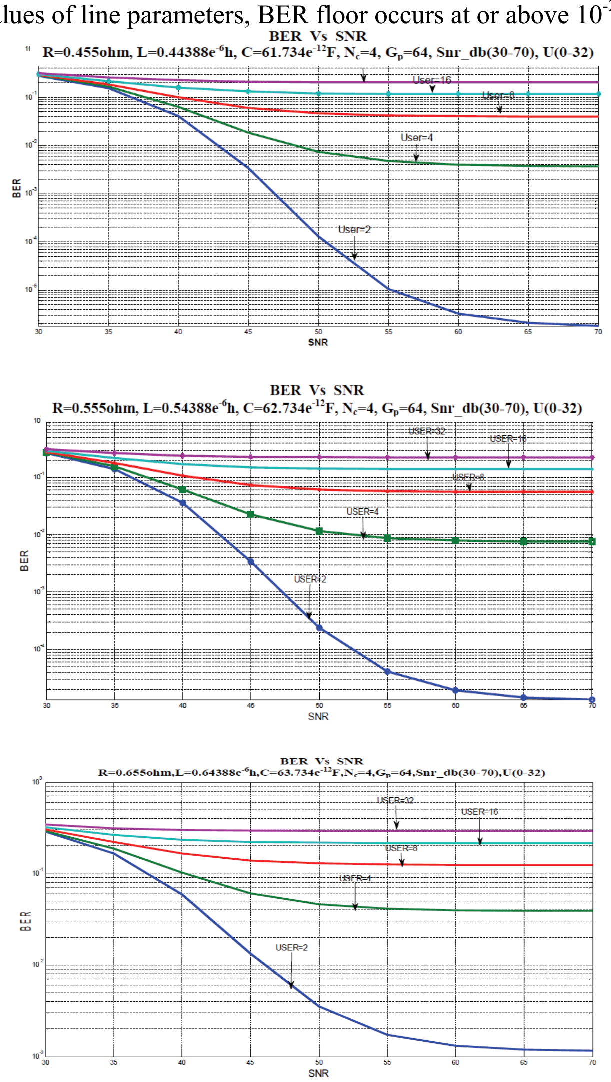

Figure . 5 Plots of BER Vs SNR for different line impedances (values of R, L and C varying)

B. *BER Vs SNR for different branch lengths*

The plots of BER versus SNR for different branch lengths are depicted in Figure 6. It is noticed that for a given value of load impedance, as the number of branch lengths are increased, the BER floor occurs at higher values. For BER ≤ 10^{-2}, the number of users that can be supported is less than 4.

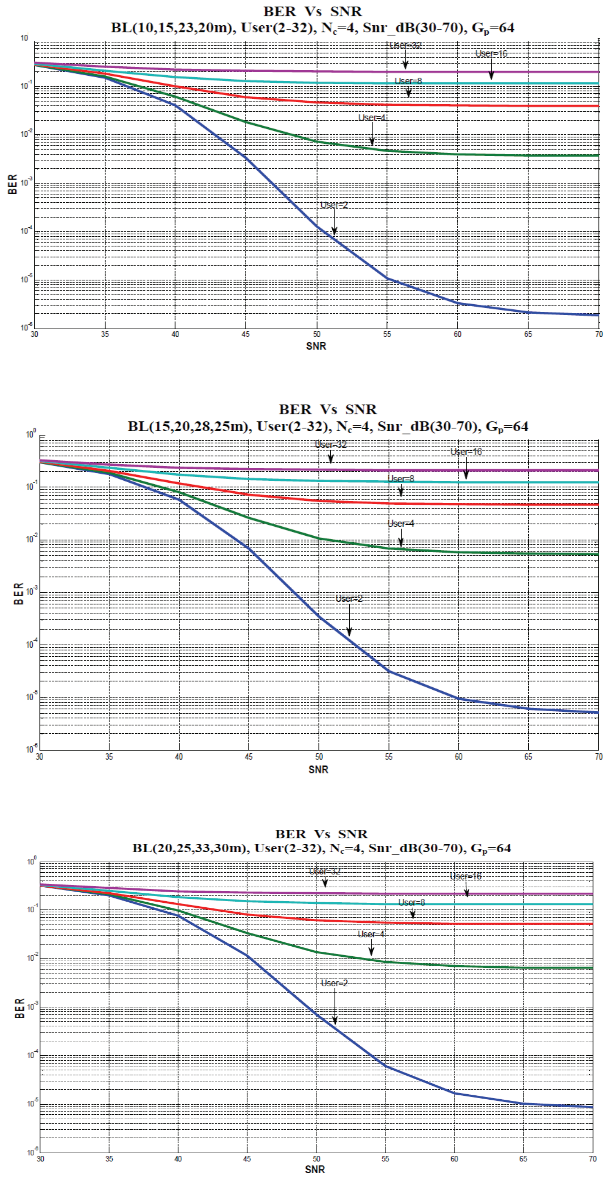

Figure. 6 Plots of BER Vs SNR for different branch lengths

C. *BER Vs SNR for different source impedances*

The plots of BER versus SNR with various source impedances and number of user as a parameter are shown in Figure 7 with other parameters as before. It is found that as the source impedance is increased, there are improvements in BER performance.

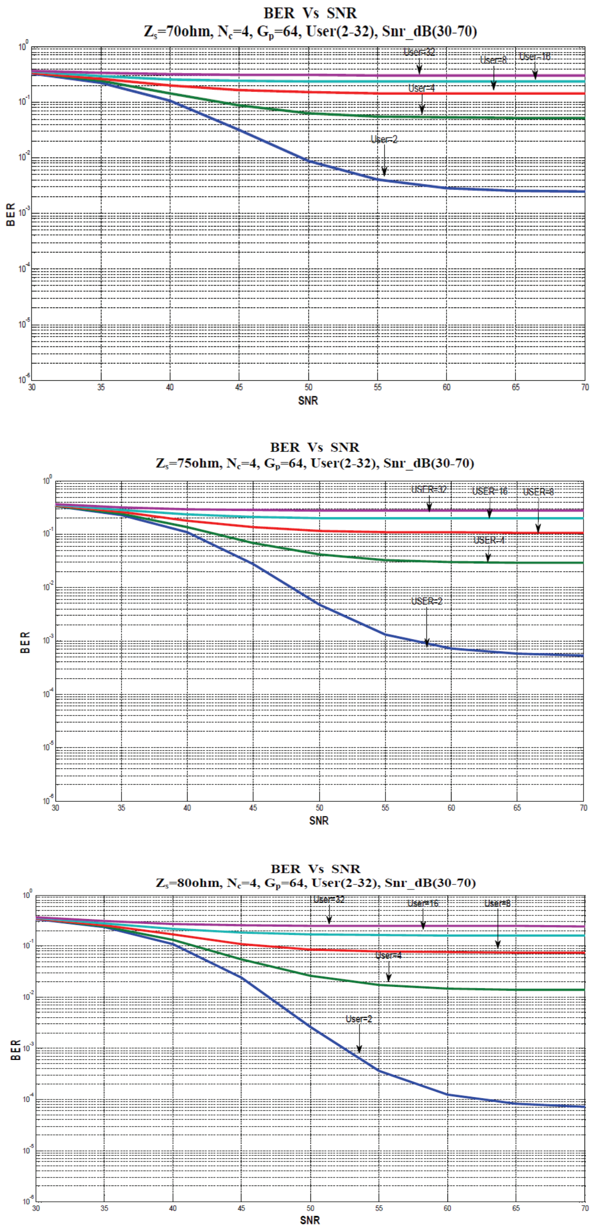

Figure. 7 Plots of BER Vs SNR for different source impedances

V. CONCLUSIONS

An analytical model is developed and a theoretical analysis is carried out to evaluate the performance of a power line communication system with multicarrier DS-CDMA under the influence of channel effects. The analysis results in the development of an analytical expression for the SINR and BER at the output of an MC-DS-CDMA receiver. The results are evaluated in terms of BER performance considering various system parameters and channel parameters. The computed results show that there is deterioration in BER performance due to channel parameters. BER performance deteriorates with the increase of line impedances, number of branches, and branch lengths. The results show that performance can be improved by increasing the source impedances.

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