

Performance Analysis of MC-SS for the Indoor BPLC Systems

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Abstract—power-line networks are promise infrastructure for broadband services provision to end users. However, the network performance is affected by stochastic channel changing which is due to load impedances, number of branches and branched line lengths. It has been proposed that multi-carrier modulations techniques such as orthogonal frequency division multiplexing (OFDM), Multi-Carrier Spread Spectrum (MC-SS), wavelet OFDM can be used in such environment. This paper investigates the performance of different indoor topologies of power-line networks that uses MC-SS modulation scheme. It is observed that when a branch is added in the link between sending and receiving end of an indoor channel an average of 2.5dB power loss is found. In additional, when the branch is added at a node an average of 1dB power loss is found. Additionally when the terminal impedances of the branch change from line characteristic impedance to impedance either higher or lower values the channel performances were tremendously improved. For example changing terminal load from characteristic impedance ($85\ \Omega$) to $5\ \Omega$ the signal to noise ratio (SNR) required to attain the same performances were decreased from 37dB to 24dB respectively. Also, changing the terminal load from channel characteristic impedance ($85\ \Omega$) to very higher impedance ($1600\ \Omega$) the SNR required to maintain the same performances were decreased from 37dB to 23dB. The result concludes that MC-SS performs better compared with OFDM techniques in all aspects and especially when the channel is terminated in either higher or lower impedances.

Keywords—Communication channel model; Broadband Power-line communication; Branched network; OFDM; Delay Spread, MC-SS; impulsive noise; load impedance

I. INTRODUCTION

POWER-LINE is an interest infrastructure for broadband communication services provision. However, a number of challenges still exist as far as data transfer through such network is concern. The power line infrastructure varies from region to region and country to country [1]. In this paper we consider the Broadband Power-Line Communication (BPLC) system for indoor channel used in Tanzania power-line network. The number of interconnected branches in the link between sending and receiving ends, different terminal loads and branch lengths cause multipath (due to transmission and reflection of signals between the transmission line segments) characteristics similar to wireless channels[2]. This multipath causes degradation in the channel performances. To cope with such behavior different Multi-Carrier modulations such as Multi-Carrier Spread Spectrum (MC-SS), Discrete Multi-tone

(DMT), Orthogonal Frequency Multiplexing (OFDM), and wavelet OFDM, including Direct Sequence Spread Spectrum (DSSS) have been proposed [3]. There have been various studies on the channel performance based on OFDM Systems, the studies can be found in Hsu *et al* [4], Amirshahi *et al* [5], Ma *et al* [6], Andreadou and Pavlidou [7], Babic *et al* [8], Anatory *et al*[2] etc. Many studies on the channel performance have been focusing on impulsive noise. The influences of load impedances, line length and branches on the performance of indoor BPLC based on OFDM techniques were invested in [2]. It was observed that when the line terminal impedances are close to either short or open circuits OFDM techniques performance tends to be degraded, the same applied when there is an increase in the number of branches either at single node or distributed between sending and receiving ends. It was observed that to overcome such poor performance concatenated Reed Solomon codes and interleaved Viterbi techniques are necessary [2, 9-10]. Although many researches have proposed OFDM scheme to be used in the BPLC system due to its robustness to frequency selectivity, it has been noted that OFDM scheme has disadvantages such as difficulty in subcarrier synchronization, sensitivity to frequency offset and nonlinear amplification. This result is due to the fact that it is composed of a lot of subcarriers with their overlapping power spectra and exhibits a non-constant nature in its envelope. Because, MC-SS techniques have a combination of OFDM, inevitably have the same drawbacks. However, it has said that the combination of OFDM signaling and spread spectrum scheme has one major advantage that it can lower the symbol rate in each subcarrier so that a longer symbol duration makes it easier to quasi-synchronize the transmission[11,12]. In this study MC-SS modulation scheme is used to check the improvements in the performance of indoor BPLC system, compared with our previous study using OFDM which is presented in Anatory *et al* [2]. The observations from this paper can be used as improvement for the implementations of BPLC systems.

II. ADOPTED POWER-LINE CHANNEL AND NOISE MODEL

A. Channel Model

In this paper the generalized TL theory channel model proposed in [9-10, 13] for a power-line network with distributed branches (as shown in Fig. 1) is used. Consider the Power line network as shown in Fig. 1. Note that the procedure for the obtaining the transfer function is the same i.e. writing the voltage and current boundary conditions at all the nodes and solving for the unknown modal currents. The transfer function for the voltage between any load point Z_{nm} and the sending end

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is given by (1). In (1) Z_{nm} , Z_{nm} , γ_{nm} , and L_{nm} are characteristic impedance of line segment nm , terminal load impedance of line nm , propagation constant of line segment nm , and shortest length of line segment from transmitting to receiving ends respectively. In equation (1), $A_1^+ = Z_{C11} + Z_s$ and $A_1^- = Z_{C11} - Z_s$. Z_s is source impedance, the channel models factors β_{nm} and β_{11} are well documented in Anatory *et al* [9, 10, and 13]. In fig. 1, n is the referenced number of distributed nodes such that $n=1, 2, 3, \dots, M_T$, and M_T is total number of distributed branches. The parameter m is the referenced number of branches at a node such that $m=1, 2, 3, 4, \dots, N_T$, and N_T is total number of branches at a node n .

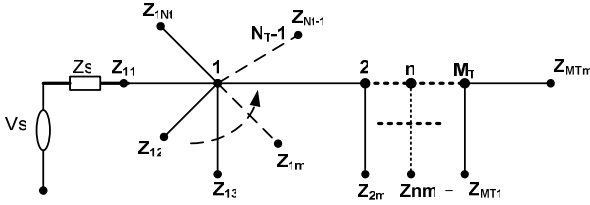


Fig. 1 Power-line network with distributed branches [10]

$$H_{nm}(f) = \frac{Z_{C11} + Z_s}{Z_{C11}} Z_{Cnm} \left(e^{-\gamma_{nm} L_{nm}} \beta_{nm} + e^{\gamma_{nm} L_{nm}} \right) A_{nm} \frac{1}{A_1^+ \beta_{11} + A_1^-} \quad (1)$$

B. Noise in Power-Line Networks

Power-line channel suffers from impulsive noise interferences that are generated from connected electrical devices/loads. The impulsive noise may cause bit or burst errors in data transmission and can affect communications in the indoor power-line channels [2]. Middleton's Class A noise model is one of the appropriate models for impulsive noise environments [14-16]. However, noise in power-line environment is a combination of impulsive and background noise. Based on Middleton's Class A noise model, the combination of impulsive plus background noise is a sequence of i.i.d complex random variables with the probability density function (PDF) of Class A noise as given by (2). Where m is the number of impulsive noise sources 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 a typical impulse) as shown in (3). In (4) Γ is the Gauss impulsive power ratio (GIR) which represents the ratio between the variance of Gaussian noise components σ_g^2 and the variance of impulse component σ_z^2 . The variance of noise σ_z^2 is given (5) [15].

$$p_z(z) = \sum_{m=0}^{\infty} \frac{\alpha_m}{2\pi\sigma_m^2} \exp\left(-\frac{z^2}{2\sigma_m^2}\right) \quad (2)$$

$$\alpha_m = e^{-A} \frac{A^m}{m!} \quad (3)$$

$$\sigma_m^2 = \sigma_g^2 \frac{\left(\frac{m}{A}\right) + \Gamma}{\Gamma} \quad (4)$$

$$\sigma_z^2 = E\{z^2\} = \frac{e^{-A} \sigma_g^2}{\Gamma} \sum_{m=0}^{\infty} \frac{A^m}{m!} \left(\frac{m}{A} + \Gamma\right) \quad (5)$$

III. MULTI-CARRIER SPREAD SPECTRUM MODULATION

MC-SS modulation scheme can be seen as a combination of direct sequence spread spectrum and OFDM modulation. The idea behind MC-SS is to spread the information symbol over the different frequencies by transmitting each chip over different frequencies. Fig. 2 and 3 show the configuration of MC-SS transmitter and receiver systems respectively [10, 17].

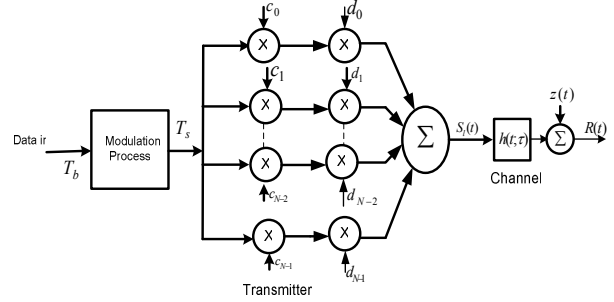


Fig. 2 General configuration of MC-SS transmitter [10, 17]

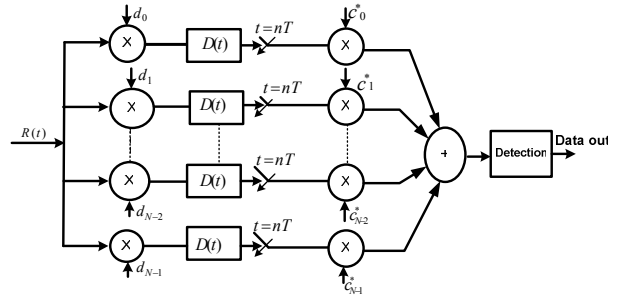


Fig. 3 General configuration of MC-SS correlation receiver [10, 17]

In fig. 2 The parameters $d_0 = e^{j2\pi f_o t}$, $d_1 = e^{j2\pi f_1 t}$, $d_{N-2} = e^{j2\pi f_{N-2} t}$ and $d_{N-1} = e^{j2\pi f_{N-1} t}$. In fig. 3, the parameters $d_0 = e^{-j2\pi f_o t}$, $d_1 = e^{-j2\pi f_1 t}$, $d_{N-2} = e^{-j2\pi f_{N-2} t}$,

$d_{N-1} = e^{-j2\pi f_{N-1} t}$ and $D(t) = \int_T (\cdot) dt$. The parameter T_s and T_b is the symbol and bit duration respectively. C_k is the k^{th} spread element.

In MC-SS transmission techniques the complex-valued data symbol obtained from the baseband modulator is spread by a spreading code and then transmitted through the different subcarriers with each chip on a different subcarrier. The baseband modulator can be either Phase shift keying (PSK) or Quadrature Amplitude Modulation (QAM) or Phase Amplitude Modulation (PAM) [10, 17]. Considering power line channel with impulse response $h_i(t)$ and τ_i the time delay of path i , the multi-path spread spectrum received signal is given as in (6).

$$r_i(t) = \sum_{i=0}^{L-1} h_i s_i(t - \tau_i) + z(t) \quad (6)$$

Where $s_i(t)$ and $z(t)$ are the equivalent low-pass of the transmitted signal and complex Gaussian noise process respectively, $k=0, 1, \dots, N-1$.

$$y_k(n) = H_k(n)s(n)c_k + z_k(n) \quad (7)$$

If we assume that the guard interval is larger compared to maximum delay spread of power-line channel, the output sample of the correlation receiver, during the n^{th} symbol interval can be written as in (7), whereby $k=0, 1, \dots, N-1$. The parameter $z(n)$ is complex variable representing noise in power-line channel, $s(n)$ is the baseband modulated symbol during the n^{th} symbol interval, and $H_k(n)$ is a sampled channel transfer function at subcarrier k , and is given by (8), since the sampled noise are complex random variables, optimum signal spreading is obtained as in (9), which can be expanded as (10). The signal to noise ratio per symbol is directly obtained from (10) and can be represented as (11) [10, 17].

$$H_k(n) = \sum_{i=0}^{L-1} h_i e^{-j2\pi k \tau_i / T_s} \quad (8)$$

$$y(n) = \sum H_k^*(n) c_k^* y_k(n) \quad (9)$$

$$y(n) = \left(\frac{1}{N} \sum_{k=0}^{N-1} |H_k(n)|^2 \right) s(n) + \sum_{k=0}^{N-1} H_k^*(n) c_k^* z_k(n) \quad (10)$$

$$SNR = \left(\frac{1}{N_c} \sum_{k=0}^{N-1} |H_k(n)|^2 \right) \frac{E_s}{N_o} \quad (11)$$

The performance indication of modulation scheme in any communication channel is through bit error rate performance. In this paper the MC-SS based on BPSK modulation is used. The bit error rate performance of BPLC based MC-SS as a modulation scheme is given by (12) [17]. The parameters E_s , N_m , H_k , and N_c are the energy of the signal, noise power, sub-channel response and number of subcarrier respectively. Sometimes in Multi-Carrier spread spectrum normally to ensure frequency non selective fading, the original data sequence is first converted into parallel sequences, and then each sequence is mapped onto processing gain.

$$P_b = \sqrt{2 * \left(\frac{1}{N} \sum_{k=0}^{N-1} |H_k(n)|^2 \right) \frac{E_s}{N_m}} \quad (12)$$

IV. PERFORMANCE ANALYSIS

A. Performance of MC-SS System

The typical indoor channel used in residences and offices [1], which connects appliances using cables having cross section 2.5mm^2 the separation 3mm as discussed in [1, 2]. The transmission line parameters are ($L_e = 0.44388\mu\text{H/m}$,

$C_e = 61.734\text{pF/m}$). The power-line channel configuration under investigation is given in Fig. 4 with $Z_s = Z_L = 85\Omega$. We investigate the variations in the number of branches in the link between A and N and also vary the terminal load impedances connected to the branches; finally we looked at a situation when a number of branches are changing on the same node. In additional we investigated a case whereby the branched line length is changing which also a real scenario in the practical power-line environment.

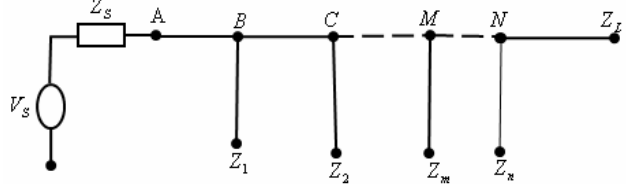


Fig. 4: Power-line network with distributed

We consider an MC-SS system with total frequency band $B = 99.9\text{MHz}$. In the MC-SS system, the set of subcarrier frequencies should be chosen so that signals at different frequencies do not interfere with each other (orthogonally property). The minimum required frequency separation is $1/T_s$. For the case of a system with such frequency bands, a single-carrier system would have symbol time T_s of 1ns . According to the investigations regarding the maximum delay spread [18] (time span of channel impulse response) for indoor power-line channels in Tanzanian network it is found to have T_m of $1\mu\text{s}$ [18]. In the proposed band there would be severe inter-symbol interference (ISI) [19-20].

We assumed an MC-SS modulation system with BPSK, considering as delay spread T_m of $1\mu\text{s}$, the channel coherence bandwidth B_c is 1MHz . To ensure flat fading on each sub-channel, we take $B_N = B/N_c = 0.1B_c$. Thus number sub-channels N_c needed are 999. In the actual implementations of Multi-Carrier modulation, N_c must be a power of 2 for the Discrete Fourier Transformation (DFT) and Inverse of Discrete Fourier Transformation (IDFT) operations, in which case $N_c = 1024$ is appropriate. So the MC-SS symbol duration is $T_N = N \cdot T_s = 10.24\mu\text{s}$. These design parameters are used in indoor cases analysis to follow in the paper.

B. Performance of MC-SS in the Branched Networks

1) A Case of Distributed Branches

To determine the influence of branches, the power-line configuration with distributed branches as in Fig. 4 was considered. The branches between point A and L were equally distributed between transmitting and receiving ends. The transmitter and receiver loads were terminated in the line characteristic impedances and the system was assumed to be synchronized. The line length between point A and L was 20m , while the branch line lengths were kept at 10m . The branches were varied as 2, 4, and 8 and all load terminals were terminated in characteristic impedances of the branch. For each case the channel transfer function $H(f)$ was determined using (1) and the transfer function was sampled as $H_k(n)$ indicated in (8) and (12) was used to evaluate the performance.

The channel frequency responses were sampled at 1024 subcarrier as obtained in the previous section. For the case of noise N_m the square root noise variance in (2) was used. In (2) the value of A and GIR was 0.1 and 0.1, respectively and m is taken as 3 [16]. Fig. 5 shows the performance of the MC-SS system for various number of branches. It can be observed that to attain a bit error probability of 10^{-10} the SNR per bit of 31 dB, 37 dB, and 44 dB are needed for 2, 4, and 8 branches, respectively. The observation indicates that from 2 branches to 4 branches the average power needed is 3dB/branch. However, as the number of branches increases more the average power needed tends to decrease. For example for a channel with 8 branches the average power needed per branch is about 2.1dB/branch so that sustained communication is still maintained. Comparing with the previous studies by Anatory and Theethayi [2] it indicates that using MC-SS the improvement is about 2dB, 5dB and 14dB for 2, 4 and 8 branches respectively comparing with OFDM system.

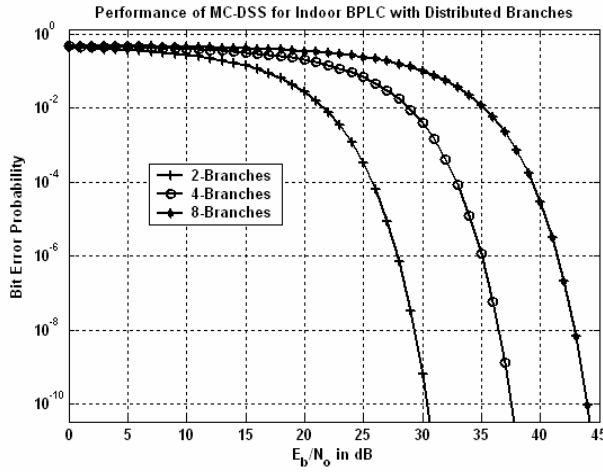


Fig. 5 Simulation results for the Multi Carrier Spread Spectrum system with BPSK modulation for indoor PLC channel for various number of branches terminated in characteristic impedances

2) A case of number of branches at a node

In some cases in the houses and offices power-lines are concentrated at a single node. It is thus appropriate to investigate the influence of such topologies. To determine the influence of branches at a node, the power-line configuration shown in Fig. 6 was considered. In fig. 6, Z_s , Z_{Lm} are the source and terminal load impedance of line m , respectively. For a network with configuration as in fig. 6, the channel model is given as (13) [9-10, 13]. In (13) the parameters Z_{Cm} , Z_{C1} , γ_m are characteristic impedance of line segment m , characteristic impedance of line segment 1, and propagation constant of line segment m . In equation (13), $A_1^+ = Z_{C1} + Z_s$ and $A_1^- = Z_{C1} - Z_s$. Z_s is source impedance, the channel models factors β_m , β_1 and A_{1m} are well documented in Anatory *et al* [9, 10, and 13].

$$H_m(f) = \frac{Z_{C1} + Z_s}{Z_{C1}} Z_{Cm} \left(e^{-\gamma_m l_m} \beta_m + e^{\gamma_m l_m} \right) A_m \frac{1}{A_1^+ \beta_1 + A_1^-} \quad (13)$$

To determine the influence of number of branches at node B, the transmitter and receiver loads at D were terminated in the line characteristic impedances and the system was assumed to be synchronized. The line length between the transmitter at (point A) and D was 20m, while the branch line lengths were kept at 10m. The branches at node B were varied as 2, 4, 8 and 16 and all load terminals were terminated in characteristic impedances of the branch. For each case the channel transfer function $H(f)$ was determined using (13) and the channel was sampled as in (6). The channel frequency responses were sampled at 1024. For the case of noise N_m the square root noise variance in (5) was used. In (5) the value of A and GIR was 0.1 and 0.1, respectively and m is taken as 3 [11].

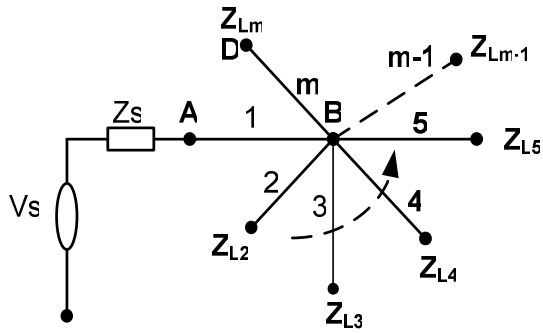


Fig. 6 Power line network with a number of branches at a single node

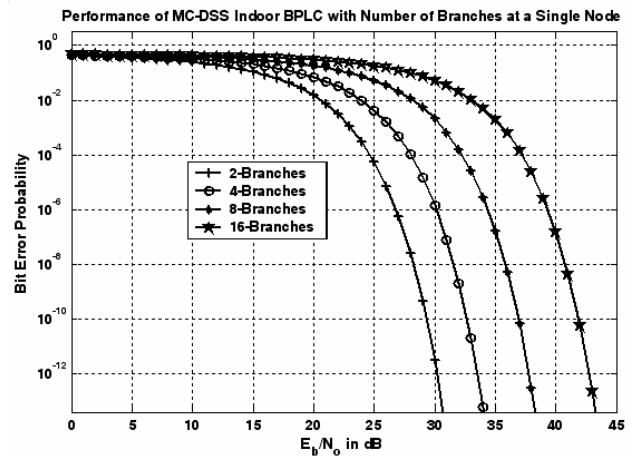


Fig. 7 Simulation results for the Multi Carrier Spread Spectrum system with BPSK modulation for indoor PLC channel for various number of branches terminated in characteristic impedances

Fig. 7 shows the performance of the MC-SS system for various number of branches. It can be observed that to attain a bit error probability of 10^{-10} the SNR per bit of 29 dB, 33 dB, 37dB and 42 dB are needed for 2, 4, 8 and 16 branches, respectively. This indicates the average power needed per branch is about 2dB/branch, 1dB/branch and 0.5dB/branch for the branches up to 4, 8 and 16 respectively so that sustained communication is still maintained.

C. Performance for a case of Branched Line Length

To determine the influence of branched line length the same configuration as in fig. 4 with four branches equally distributed between A and L was considered. The line length between point A and L was 20m, while the branch lengths were varied as 5m, 10m, 15m, and 20m. The transmitter and receiver loads were terminated in the line characteristic impedances and the system was assumed to be synchronized while the branched loads terminated in 50Ω (chosen for having some reflections). Fig. 8 shows the performance of the MC-SS system modulated with BPSK for various branch lengths. It is seen from Fig. 8 that for indoor channels the influence of branched line length is almost negligible for MC-SS systems.

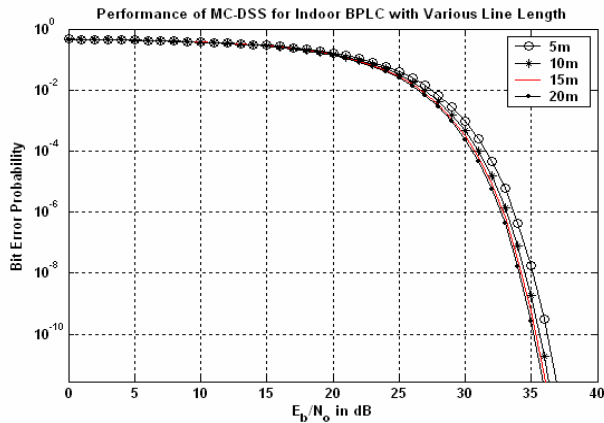


Fig. 8 Simulation results for the Multi Carrier Spread Spectrum system with BPSK modulation for indoor PLC channel with four distributed branches terminated in characteristic impedances with various branched length

D. Performance of a network with variation of Load Impedances

Again the configuration with four distributed branches as in Fig. 4 was considered with line length between A and L as 20m with branch lengths as 10m. The branches between point A and L were equally distributed between transmitting and receiving ends. The transmitter and receiver loads were terminated in the line characteristic impedances and the system between transmitting and receiving ends were assumed to be synchronized.

1) A case of Low impedance Loads

We consider first the low impedance loads (loads less than branch line characteristic impedance). The load impedances at all terminals were varied as 5Ω, 15Ω, 45Ω, and 85Ω. Fig. 9 shows the performance of the MC-SS system with various load impedances.

It is observed that the poor performance can be obtained when the channel is terminated in characteristic impedances wherein the bit error probability is 10^{-10} at a SNR per bit of 38 dB. When the load impedance decreases by 40Ω from line characteristic impedance, the power improvement is about 0.075 dB/Ω but when the impedance was decreased by 60Ω, the power improvement is about 0.1833dB/Ω. The good performance is obtained when the channel is terminated in 5Ω which is 24dB. This indicates that as load impedance

approaches a short circuit it leads to an improvement system performance. The observation from this results is showing that MC-SS systems is superior in multipath environment compared with OFDM system as reported in Anatory et al[2].

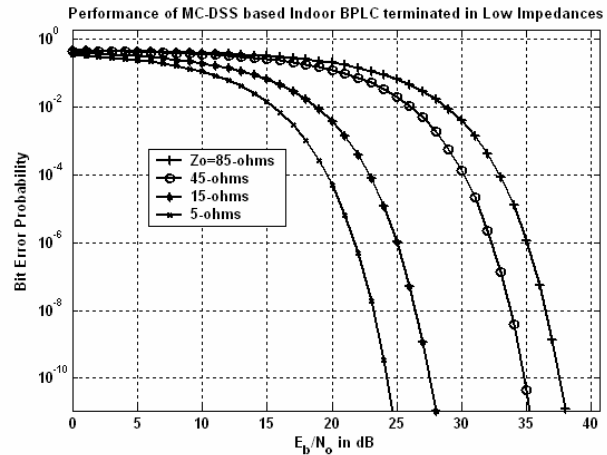


Fig. 9 Simulation results for the Multi Carrier Spread Spectrum system with BPSK modulation for indoor PLC channel for various low load impedances at branch terminations

2) A case of High impedance Loads

We now consider the high impedance loads (impedances higher than the line characteristic impedance). The load impedances at all terminals were varied as 85 Ω, 200 Ω, 400 Ω, and 1600 Ω. Fig. 10 shows the performance of the MC-SS system for various impedances. A poor channel performance is seen for channel characteristic impedance (85Ω) terminations with the bit error probability of 10^{-10} at a SNR per bit of 38 dB. When the load impedance increases beyond 200 Ω the power gain is about 0.06 dB/Ω and if it increases above 400 Ω the power gain is about 0.09 dB/Ω indicating that the performance is improving. When the load impedance is 1600 Ω the SNR required to maintain the same performance is 23dB which is about 15dB power gain, which shows that as the load impedance approaches open circuit the performance is improving. This observation is concluding that the MC-SS system is performing better in multipath environment of power-line compared with OFDM which normally tends to be degraded in performance as either the network approaches short circuits or open circuit [2].

V. CONCLUSION

In this paper, it is shown that the variations in number of distributed branches in the link between the transmitting and receiving ends of an indoor power line channel result in poor channel performance for MC-SS based on BPSK as subcarrier, however the performance is better in comparison with uncoded OFDM system[2]. It is found that there is a 2.5 dB power loss when numbers of branches are increased in the link compared to 4dB which was reported in Anatory *et al*[2] using OFDM system. Addition of branch at a single node the maximum power loss is 2dB. When the termination load

impedances are less than the characteristic impedance there is a power gain of 0.2 dB/ Ω and power improvement is largely increases when the load impedances are much lower than the branch characteristic impedance. When the load impedances are higher than the branch characteristic impedance the power gain is 0.1 dB/ Ω and power gain largely increases when the load impedances are much higher than the branch characteristic impedance. The performance observed in all aspects is better compared with OFDM counterparts. The performance in this study is comparable with OFDM system when used with concatenated Reed-Solomon/Viterbi coding [2]. This concludes that MC-SS is appropriate techniques to be used in the BPLC systems.

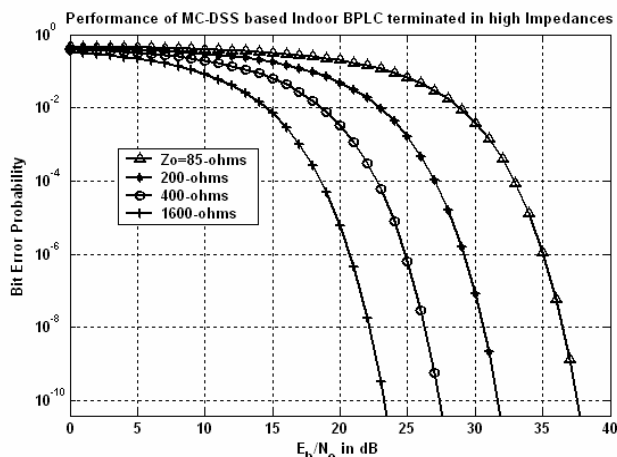


Fig. 10 Simulation results for the Multi Carrier Spread Spectrum system with BPSK modulation for indoor PLC channel for various high impedances at branch terminations

REFERENCES

- [1] J. Anatory, N. Theethayi, R. Thottappillil, M. M. Kissaka, and N. H. Mvungi, "The effects of load impedance, line length and branches in the BPLC-transmission-line analysis for indoor voltage channel," *IEEE Trans. Power Del.*, vol. 22, no. 4, pp. 2150–2155, Oct. 2007.
- [2] J. Anatory, N. Theethayi, and R. Thottappillil "Effects of Multipath on OFDM Systems for Indoor Broadband Power-Line Communication Networks", *IEEE Transactions on Power Delivery*, Vol. 24, No. 3, pp. 1190-1197, July, 2009.
- [3] H. Hrasnica, H. Abdelfattah and L. Ralf, "Broadband Powerline Communications Networks-Network Design", John Wiley & Sons, Ltd, 2004.
- [4] C. Hsu, N. Wang, W. Chan and P. Jain, "Improving a Power-line Communications Standard with LDPC Codes", *EURASIP Journal on Advances in Signal Processing*, Vol. 2007, pp. 1-9.
- [5] P. Amirshashi, S. M. Navidpour and M. Kavehrad, "Performance Analysis of Uncoded and Coded OFDM Broadband Transmission Over Low Voltage Power-Line Channels with Impulsive Noise, *IEEE Transactions on Power Delivery*, Vol. 21, No. 4, October, 2006.
- [6] Y. H. Ma, P. L. So, and E. Gunawan, "Performance Analysis of OFDM Systems for Broadband Power Line Co", *IEEE Transactions on Power Delivery*, Vol. 23, No. 1, January, 2008, pp. 132-139
- [7] N. Andreadou, F.-N. Pavlidou, "Performance of Array Codes on Power Line Communications Channel", *In Proceedings of the 12th IEEE International Symposium on Power-Line Communications and its Applications (ISPLC) 2008*, Jeju Island, Korea, 2-4 Apr 2008.
- [8] M. Babic, J. Baush, T. Kistner and K. Dostert, "Performance Analysis of Coded OFDM Systems at Statistically Representative PLC Channels, *IEEE-ISPLC 2006*, , pp 104-109, Orlando, FL, 2006.
- [9] J. Anatory, N. Theethayi, and R. Thottappillil and N.H. Mvungi "A Broadband Power-Line Communication System Design Scheme for Typical Tanzanian Low Voltage Network", *IEEE Transactions on Power Delivery*, Vol. 24, No. 3, pp. 1218-1224, July, 2009
- [10] J. Anatory and N. Theethayi, *Broadband Power-Line Communication Systems: Theory and Applications*, WIT Press, UK, May, 2010, ISBN 978-1-84564-416-1
- [11] S. Hara and R. Prasad, "Overview of Multicarrier CDMA," *IEEE Communications Magazine*, pp. 126-133, December, 1997
- [12] E. Lemois and F. Buda, New Advances in Multi-Carrier Spread Spectrum techniques for tactical Communications, *Proceeding of IEEE Military Communications Conference*, pp. 664-668 , Vol. 2, Boston, MA, USA, October, 1998
- [13] J. Anatory, N. Theethayi, and R. Thottappillil "Power-Line Communication Channel Model for Interconnected Networks - Part I: Two Conductor System", *IEEE Transactions on Power Delivery*, Vol. 24, No. 1, pp. 118-123, January 2009.
- [14] D. Middleton, "Statistical-physical model of electromagnetic interference, *IEEE Trans. Electromagnetic Compat.*, vol. EMC-19, no. 3, pp. 106-126, August 1977.
- [15] D. Middleton, "Procedures for determining the parameters of the r -st-order canonical models of Class A and Class B electromagnetic interference [10], *IEEE Trans. Electromagn. Compat.*, vol. EMC-21, no. 3, pp. 190-208, August 1979.
- [16] T. Fukami, D. Umehara, M. Kawai, and Y. Morihiro, "Noncoherent PSK Optimum Receiver over Impulsive Noise Channels", *International Symposium of Information Theory and Its Applications 2002*, Xi'an, PRC, pp. 235-238, Oct. 2002.
- [17] L. Ahlin, J. Zander and B. Slimane, *Principles of Wireless Communications*, Denmark Narayana Press, 2006.
- [18] J. Anatory, N. Theethayi, and R. Thottappillil "Channel Characterization for Indoor Power-Line Networks", *IEEE Transactions on Power Delivery*, October, Vol. 24, No. 4, pp. 1883-1888, 2009
- [19] A. Goldsmith, *Wireless Communications*, Cambridge University Press, 2005.
- [20] R. Prasad, *OFDM for Wireless Communications Systems*, Boston, MA, Artech House, 2004.

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