Analytical bit error rate performance evaluation of an orthogonal frequency division multiplexing power line communication system impaired by impulsive and Gaussian channel noise

Munshi Mahbubur Rahman[1,2], *Satya Prasad Majumder*[1]

[1]*Department of EEE, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh*
[2]*Military Institute of Science and Technology, Dhaka 1216, Bangladesh*
E-mail: mmr@eece.mist.ac.bd

Published in *The Journal of Engineering*; Received on 28th August 2014; Accepted on 10th December 2014

Abstract: An analytical approach is presented to evaluate the bit error rate (BER) performance of a power line (PL) communication system considering the combined influence of impulsive noise and background PL Gaussian noise. Middleton class-A noise model is considered to evaluate the effect of impulsive noise. The analysis is carried out to find the expression of the signal-to-noise ratio and BER considering orthogonal frequency division multiplexing (OFDM) with binary phase shift keying modulation with coherent demodulation of OFDM sub-channels. The results are evaluated numerically considering the multipath transfer function model of PL with non-flat power spectral density of PL background noise over a bandwidth of 0.3–100 MHz. The results are plotted for several system and noise parameters and penalty because of impulsive noise is determined at a BER of 10^{-6}. The computed results show that the system suffers significant power penalty because of impulsive noise which is higher at higher channel bandwidth and can be reduced by increasing the number of OFDM sub-carriers to some extent. The analytical results conform well with the simulation results reported earlier.

1 Introduction

After many years of development, the power line communication (PLC) technology has emerged as a very attractive alternative for the provision of broadband communications services to residential and business users over medium and low-voltage power lines (PLs) [1–6]. Research work is continued to determine accurate channel models for the PL network during past decade. The economic and operational viability of using this technology leans on the current availability of low-cost PLC equipment and solutions, besides the utilisation of the power network infrastructure already in place. For a PLC network, the available infrastructures are indoor and outdoor and the usable frequency band is narrowband and broadband. However, it is observed that a number of challenges such as noise, fading, attenuation, multipath propagation and so on exist [6–10] which limit the available data rate.

Most of the available PLC systems provide a maximum data rate of more than several megabits per second. However, the PL grid can be characterised as a rather hostile medium for data transmission [10] as it was originally designed for the distribution of electrical power in the frequency range of 50–60 Hz. As a result, the PLC channel faces some technical problems, such as impedance variations and mismatches, various forms of noise (mainly impulsive noise) and narrowband interferences, multipath propagation phenomena, high attenuation and other barriers of the medium.

Noise in a PL results because of the effect of corona, impulse voltages and electric arc between the lines and affects the communication link severely [8–10]. The nature of PL noise is found to be a non-white cyclostationary process. The non-white cyclostationary noise consists of stationary background noise and time variant impulsive noise with Poisson distribution. The statistical models of impulsive noise are investigated by Middleton [7] which are applicable to powerline communication (PLC) system. The impulsive noise and multipath effects are the main factors considered for degrading the PLC performance [7–11]. A number of research works are carried out on evaluation of the effect of PL noise on the performance of a PLC system [12–16].

Orthogonal frequency division multiplexing (OFDM) is a technique which separates overall transmitted data in many parallel independent sub-streams. The long symbol duration time makes OFDM perform better than single carrier scheme for multipath channel [3, 17, 18]. OFDM may perform better than single carrier when the channel is interfered by impulsive noise, since it can spread the impulsive noise over multiple symbols because of inverse fast Fourier transform. The performance of OFDM PLC system with different array coding was recently reported by computer simulation in the presence of impulsive noise with class-A channel noise model [13]. Furthermore, the influence of impulsive noise on a PLC system in the presence of background Gaussian noise is investigated by simulation using class-A channel noise model [14]. More recently, the performance of PLC system with multiple-input–multiple-output (MIMO) OFDM multicarrier modulation is reported [18] and are found to provide better performance over single carrier PLC system. Performance analysis of a PLC system with OFDM at maximal ratio receive diversity is also reported [19]. Recently, simulation results on space–time block code MIMO PLC system is reported for cancellation of impulsive noise [20]. More recently, the effect of non-white Gaussian noise on the bit error rate (BER) performance of a PLC system is reported in [21]. In this paper, we provide a detail analytical approach to find the expression of the BER in the presence of impulsive noise as well as Gaussian channel noise considering the Middleton class-A channel model for the impulsive noise. The results are evaluated numerically for various impulsive noise index and Gaussian noise to impulsive noise ratio and bandwidth, number of OFDM channels.

2 System block diagram

The block diagram of a single-input–single-output (SISO) OFDM PLC system considered for analysis is shown in Fig. 1. In the transmitter, the signal is initially processed by a serial-to-parallel (S/P) converter and then OFDM modulated. At the receiving end, signal is received through a single receiving port. The cyclic prefix of the received signal is first removed and then serial-to-parallel conversion is carried out followed by fast Fourier transform (FFT). The output sub-channel carrier frequency signals of each receiver are then multiplied by the complex conjugate of the PL channel transfer function co-efficient H_i^*

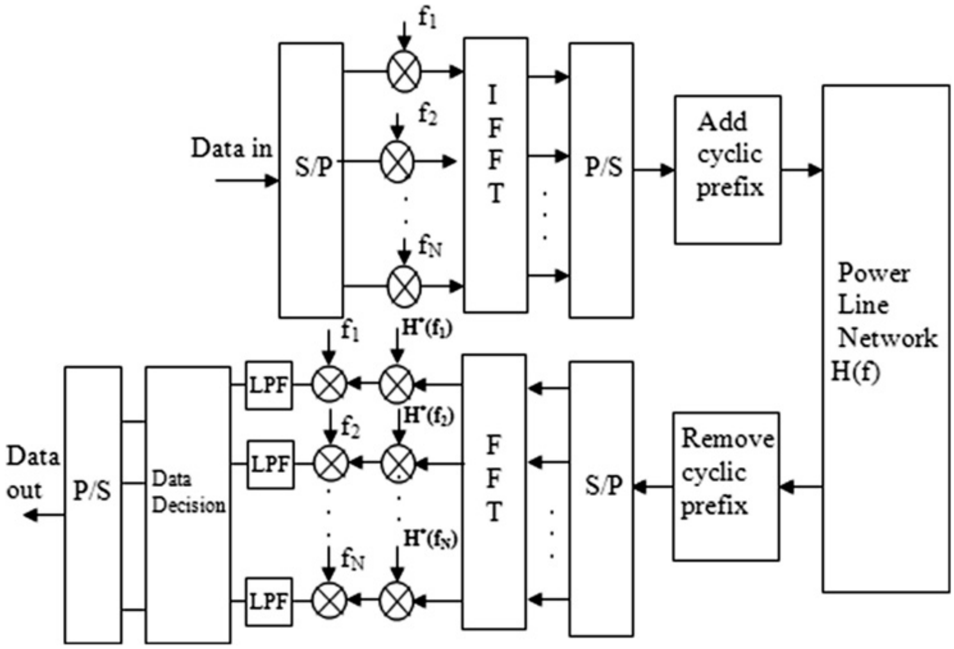

Fig. 1 *Block diagram of a SISO PLC system with OFDM*

corresponding to the ith sub-channel frequency f_i. Coherent demodulation is then carried out which is then followed by data decision and parallel to serial conversion.

3 System analysis

3.1 PL channel model

PL has frequency channel model which involves the attenuation introduced to the communication signal by cable losses as well as multipath effect. For multipath effect, the signal reaching the receiver consists of several components which have travelled through different paths. Only N dominant paths are considered for modelling. Furthermore, the signal components undergo a different amount of delay since the route they follow is not the same.

The transfer function for broadband PL in the frequency range of 0.3–100 MHz is given by [5–8]

$$H(f) = \sum_{i=1}^{L} g_i \, \mathrm{e}^{-(a_0 + a_1 f^k) d_i} \, \mathrm{e}^{-\mathrm{j}2\pi f \tau_i} \tag{1}$$

where L is the number of paths, g_i is the weighting factor for path i, a_0 and a_1 are the attenuation parameters, f is the frequency, k is the exponent of the attenuation factor (0.5–1), d_i is the length of the ith path and the corresponding delay is τ_i. The weighing factor g, is used for each path, demonstrating the reflections that occur along with it whose value is considered to be ≤ 1. The value of a_0, a_1 and g_i are given in [4, 5].

3.2 PLC noise model

In a PL channel, the noise consists of background noise and impulsive noise. Background noise has a Gaussian statistical distribution where the impulsive noise is characterised by Poisson's distribution [17].

The background noise is caused by numerous sources, such as computers dimmers or hair dryers, which can create disturbance in the frequency range 0–100 MHz and has a low power spectral density (PSD). A commonly accepted model for the background noise where the PSD is given by [3, 5]

$$R_{nb}(f) = a + b\left|f\right|^{c} \left(\frac{\mathrm{dBm}}{\mathrm{Hz}}\right) \tag{2}$$

where a, b and c are constants which can be derived from measurements and f is the frequency in megahertz (MHz). The background noise variance is given by [9]

$$\sigma_{\mathrm{b}}^2 = 2R_{\mathrm{IN}} \int_{f_1}^{f_2} 10^{\left[R_{nb}(f) - 30\right]/10} \, \mathrm{d}f \tag{3}$$

R_{IN} is the input resistance and f_1 and f_2 represents the frequency range of operation.

The total PL noise can be expressed as

$$n(t) = n_{\mathrm{b}}(t) + n_{\mathrm{imp}}(t) \tag{4}$$

According to the Middleton class-A model [7], the probability density function (PDF) of noise consisting of impulsive and background noises is given by

$$P_n(v) = \sum_{m=0}^{\infty} \frac{\mathrm{e}^{-A} A^m}{m!} \frac{1}{\sqrt{2\pi\sigma_m^2}} \, \mathrm{e}^{-(v^2/2\sigma_m^2)} \tag{5}$$

where

$$\sigma_m^2 = \left(1 + \frac{1}{\Gamma}\right)\left(\frac{(m/A) + \Gamma}{1 + \Gamma}\right) . \sigma_{\mathrm{b}}^2 \tag{6}$$

A is an impulsive noise index, σ_{b}^2 represents the variance of background PL noise and Γ is the ratio of Gaussian noise power to impulsive noise power, such that

$$\Gamma = \frac{\sigma_{\mathrm{G}}^2}{\sigma_{\mathrm{I}}^2} \tag{7}$$

3.3 Analysis of BER

Considering binary phase shift keying (BPSK) modulation with SISO PL communicating with N-OFDM subcarrier, the complex envelope of OFDM signal can be expressed as [18]

$$s(t) = \sqrt{\frac{2E_s}{T_s}} \sum_{k=0}^{\infty} \sum_{n=0}^{N-1} a_{k,n} \varphi_n(t - kT_s) \quad (8)$$

$$= \sum_{n=0}^{N-1} s_n(t) \quad (9)$$

where E_s is the energy over an OFDM symbol, T_s is the symbol period $a_{k,n}$ carries the information to be sent over the kth symbol interval $t \in [kT_s, kT_s + T_s]$ and the nth sub-band ($n = 0, 1, 2, \ldots, N-1$), N being the number of OFDM subcarrier, $v_n(t)$ is the complex envelope of the signal transmitted in the nth sub-band given by [11]

$$s_n(t) = \sqrt{\frac{2E_s}{T_s}} \sum_{k=0}^{\infty} a_{k,n} \varphi_n(t - kT_s) \quad (10)$$

where $\{\varphi_n(t)\}_{n=0}^{N-1}$ is a set of complex orthogonal waveform and is given by

$$\varphi_n(t) = \left\{ \exp\left[j2\pi \left(n - \frac{N-1}{2} \right) t/T_s \right] \right\}, \quad t \in [0,\ T_s] \quad t \notin [0,\ T_s] \quad (11)$$

Each waveform in the set $\{s_n(t)\}_{n=0}^{N-1}$ corresponds to a distinct (nth) subcarrier with frequency

$$f_n = f_c + \frac{2n - (N-1)}{2T_s}$$

We consider BPSK for which $a_{k,n} = \pm 1$, the received signal for the nth OFDM subcarrier can be expressed as

$$r_n(t) = \sqrt{\frac{2E_s}{T_s}} \sum_{k=0}^{\infty} a_{k,n} \varphi_n(t - kT_s) \otimes h_c(t) + n(t) \quad (12)$$

where $h_c(t)$ is the impulse response of the PLC channel, $\otimes$ denotes convolution and $n(t)$ represents the total PLC noise consisting of background noise $n_b(t)$ and impulsive noise $n_{imp}(t)$.

The received OFDM signal is processed at the receiving end to remove the cyclic prefix and then all the sub-band modulated carriers of OFDM signal are separated by S/P operation followed by FFT. The output is then given by

$$y_n(t) = \sqrt{\frac{2E_s}{T_s}} \sum_{k=0}^{\infty} a_{k,n} \varphi_n(t - kT_s) \cdot \left| H(f_n) \right|^2 + n(t) \cdot H^*(f_n) \quad (13)$$

where $H(f_n)$ is given by (1).

The signal at the output of coherent BPSK demodulator corresponding to the nth sub-band is given by

$$z_n(t) = \sqrt{\frac{2E_s}{T_s}} \sum_{k=0}^{\infty} a_{k,n} \varphi_n(t - kT_s) \cdot \left| H(f_n) \right|^2 + n_0(t) \quad (14)$$

The variance of output noise $n_0(t)$ is given by

$$\sigma_{0,m}^2 = \sigma_m^2 \cdot \left| H(f_n) \right|^2$$

The signal-to-noise ratio (SNR) at the output of coherent BPSK demodulator is then given by

$$\gamma_{n,m} = \frac{\left| \sqrt{((2E_s)/T_s)} \cdot \left| H(f_n) \right|^2 \right|^2}{\sigma_m^2 \cdot \left| H(f_n) \right|^2} = \frac{A_0^2}{\sigma_m^2} \cdot \left| H(f_n) \right|^2 \quad (15)$$

where

$$A_0 = \sqrt{\frac{2E_s}{T_s}} = \sqrt{2P_s} \quad \text{and} \quad m = 0{:}\infty$$

where P_s is the average signal power over an OFDM symbol interval.

As the PSD of the PL background noise is not flat, the noise power is computed by integrating the noise PSD over the OFDM sub-channel bandwidth for each OFDM carriers as expressed by (3). The bandwidth of an OFDM sub-channel is expressed by $\Delta f = B/N$ when B is the PLC channel bandwidth and N is the number of OFDM carriers. The noise power for the ith OFDM sub-channel is given by

$$\sigma_{bi}^2 = \int_{f_i - (\Delta f/2)}^{f_i + (\Delta f/2)} 2R_{IN} \left\{ 10^{\left[R_{nb}(f) - 30 \right]/10} \right\} df$$

and the SNR can be expressed as

$$\gamma_{n,m} = \frac{A_0^2 \cdot \left| H(f_n) \right|^2}{\sigma_m^2} = \frac{2P_s \cdot \left| H(f_n) \right|^2}{\sigma_b^2 \left[((m/A) + \Gamma)/\Gamma \right]} = \gamma_b \cdot \frac{2 \cdot \left| H(f_n) \right|^2}{\left[((m/A) + \Gamma)/\Gamma \right]}; \quad \text{as } \lambda_b = \frac{A_0^2/2}{\sigma_b^2} = \frac{P_s}{\sigma_b^2}$$

The PDF of $n_0(t)$ is given by [7, 14]

$$p(v_n) = \sum_{m=0}^{\infty} \frac{e^{-A} A^m}{m!} \frac{1}{\sqrt{2\pi\sigma_m^2}} e^{-(v_n^2/2\sigma_m^2)} \quad (16)$$

where v_n is the noise voltage.

The PDF of output voltage z_n is given by

$$p(z_n) = \sum_{m=0}^{\infty} \frac{e^{-A} A^m}{m!} e^{-(z_n - A_{0n})^2/2\sigma_m^2} \quad (17)$$

where A_{0n} is the average output voltage and $A_{0n} = A_0 \cdot |H(f_n)|$.

The probability of bit error for the nth subcarrier channel for a '1' transmitted with '0' received is given by

$$p(0/1) = \int_{-\infty}^{0} p(z_n)\, dz_n = \int_{-\infty}^{0} \sum_{m=0}^{\infty} \frac{e^{-A} A^m}{m!} e^{-(z_n - A_{0n})^2/2\sigma_m^2} dz_n = \sum_{m=0}^{\infty} \frac{e^{-A} A^m}{m!} \frac{1}{2} \operatorname{erfc}\left[\frac{\sqrt{\gamma_{nm}}}{\sqrt{2}} \right] \quad (18)$$

which is the same as $p(1/0)$.

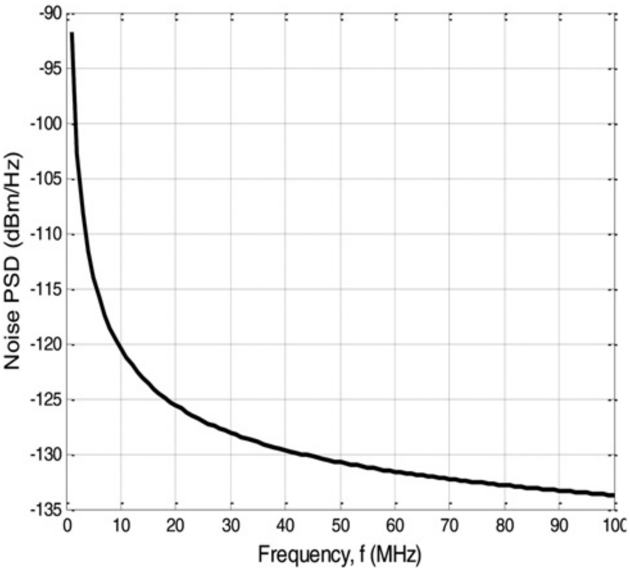

Fig. 2 *Plots of PSD of background PL noise against frequency*

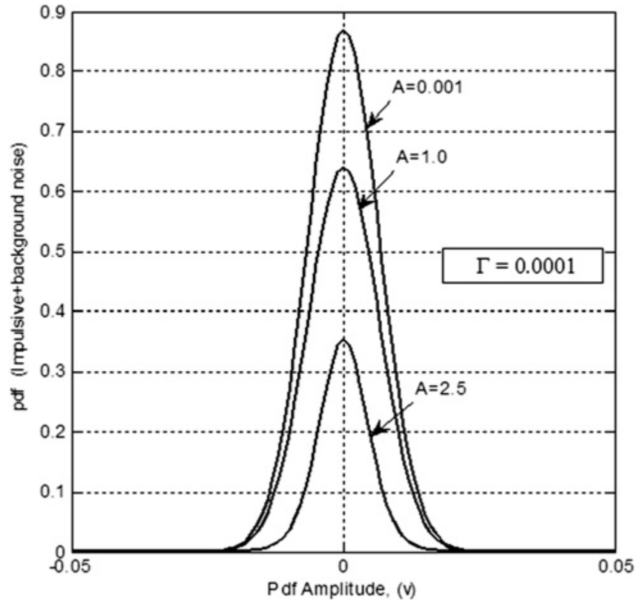

Fig. 3 *Plots of PLC noise PDF against noise amplitude*

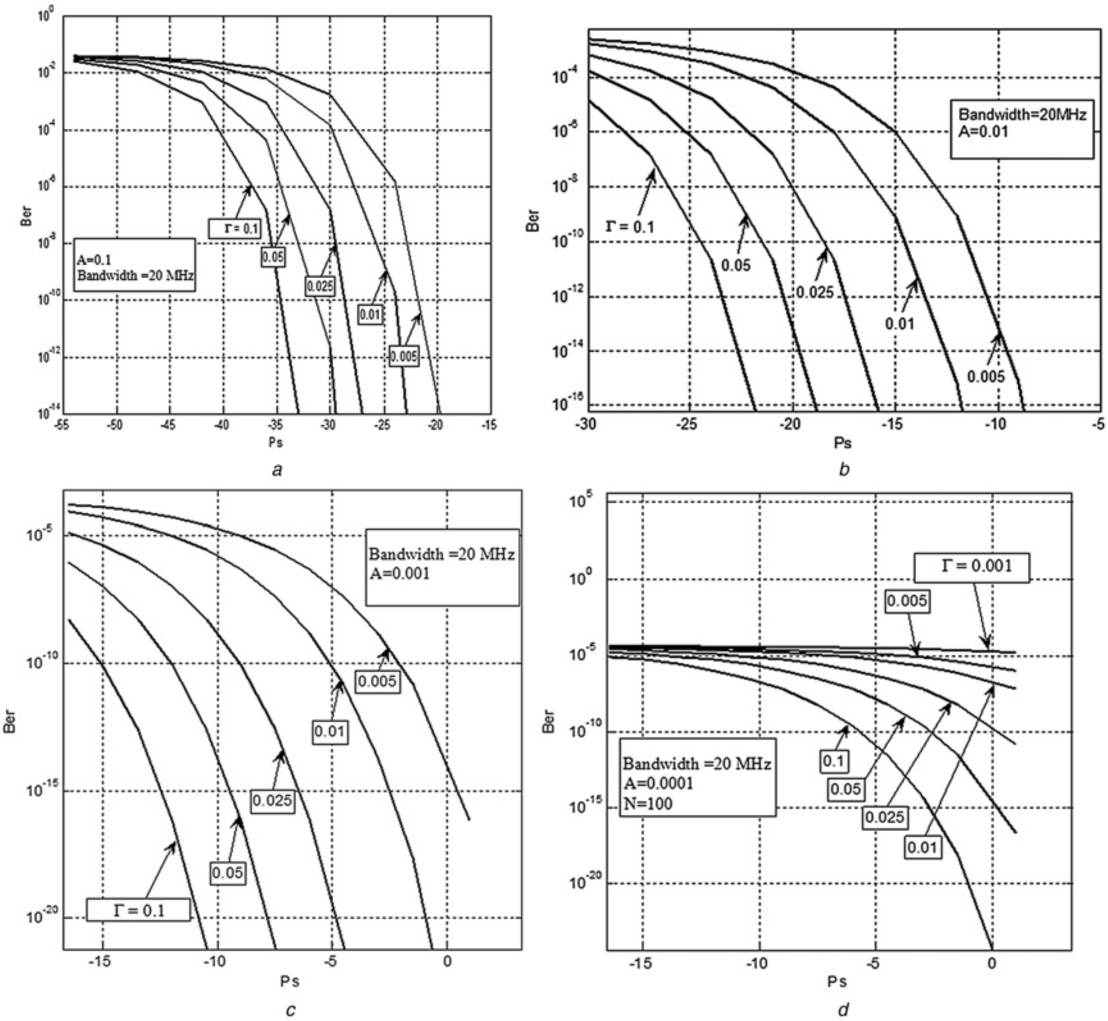

Fig. 4 *Plots of BER against received signal power P_s (dBm) are depicted*
a Plots of BER against received power, P_s for PLC system with different values Γ (where $A = 0.1$, BW = 20 MHz)
b Plots of BER against received power, P_s for PLC system with different values Γ (where $A = 0.01$, BW = 20 MHz)
c Plots of BER against received power, P_s for PLC system with different values Γ (where $A = 0.001$, BW = 20 MHz)
d Plots of BER against received power, P_s for PLC system with different values Γ (where $A = 0.0001$, BW = 20 MHz)

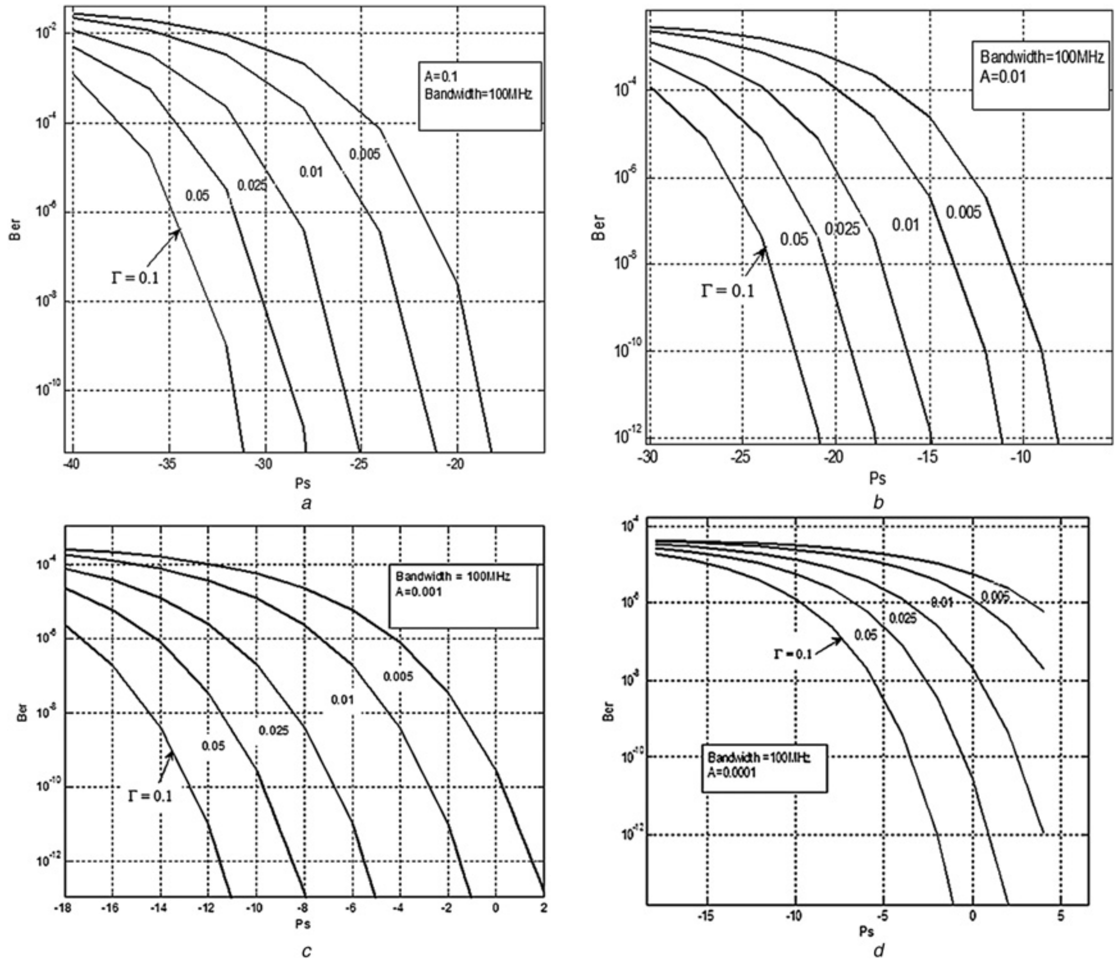

Fig. 5 *Plots of BER against received power P_s (dBm)*
a Plots of BER against received power, P_s for PLC system with different values Γ (where $A = 0.1$, BW = 100 MHz)
b Plots of BER against received power, P_s for PLC system with different values Γ (where $A = 0.01$, BW = 100 MHz)
c Plots of BER against received power, P_s for PLC system with different values Γ (where $A = 0.001$, BW = 100 MHz)
d Plots of BER against received power, P_s for PLC system with different values Γ (where $A = 0.0001$, BW = 100 MHz)

Therefore the overall BER for the *n*th sub-band channel is given by

$$p_{bn} = \sum_{m=0}^{\infty} \frac{e^{-A} A^m}{m!} . \frac{1}{2} \text{erfc} \left| \frac{\sqrt{\gamma_{n,m}}}{\sqrt{2}} \right| \tag{19}$$

$$= \frac{1}{2} e^{-A} \text{erfc} \left| \frac{\sqrt{\gamma_{n0}}}{\sqrt{2}} \right| + \frac{A}{2} e^{-A} \text{erfc} \left| \frac{\sqrt{\gamma_{n1}}}{\sqrt{2}} \right| + \frac{A^2}{2(2!)} e^{-A} \text{erfc} \left| \frac{\sqrt{\gamma_{n2}}}{\sqrt{2}} \right| + \frac{A^3}{2(3!)} e^{-A} \text{erfc} \left| \frac{\sqrt{\gamma_{n3}}}{\sqrt{2}} \right| + \cdots \tag{20}$$

The average BER of *N*-channel OFDM system is then given by

$$\text{BER} = \frac{1}{N} \sum_{n=1}^{N} P_{bn} \tag{21}$$

4 Result and discussion

On the basis of the theoretical analysis presented in Section 3, we evaluate the BER performance of a PLC system considering the effect of the PL transfer function and background noise and impulsive noise. The performance results are evaluated in terms of BER considering various channel parameters and background noise PSD over a bandwidth 0.3–100 MHz and several values of impulsive noise index. The BER performance results are evaluated for a given system bandwidth and a set of system parameters with $N = 128$.

The plots of PSD of background PLC is shown in Fig. 2 which is non-flat over the system bandwidth. It is noted that noise is dominant at lower frequencies. The plots of PDF of the PLC noise consisting of background noise and impulsive noise is shown in Fig. 3 for various impulsive noise indexes A with $\Gamma = 0.0001$. It is noted that the combined noise PDF is nearly Gaussian and has a higher variance at smaller values of A.

The plots of BER against received signal power P_s (decibel milliwatt (dBm)) are depicted in Fig. 4 for impulsive noise index $A = 0.1$, $B = 20$ MHz and Γ(Gamma) = 0.1, 0.05, 0.025, 0.01, 0.005. It is noted that there is deterioration in BER performance with decrease in the value of Γ, that is, with increase in the impulsive noise power compared with Gaussian noise. The system thus suffers because of impulsive noise at a given bandwidth. Similar plots of BER against P_s (dBm) with impulsive noise index, $A = 0.01$, 0.001 are shown in Figs. 4*b* and *c*, respectively. It is revealed from the figures that there are further deterioration in BER performance with decrease in A for the same values of bandwidth and Γ. Similar plots of BER against P_s (dBm) are shown in Fig. 4*d* for same bandwidth and $A = 0.0001$. It is observed that there is abrupt increase in BER compared with $\Gamma = 0.1$, 0.01, 0.001 as shown in Figs. 4*a*–*c*. Thus, there is drastic deterioration in BER performance with increase in the value of impulsive noise power compared with background PL noise. Similar plots of BER against

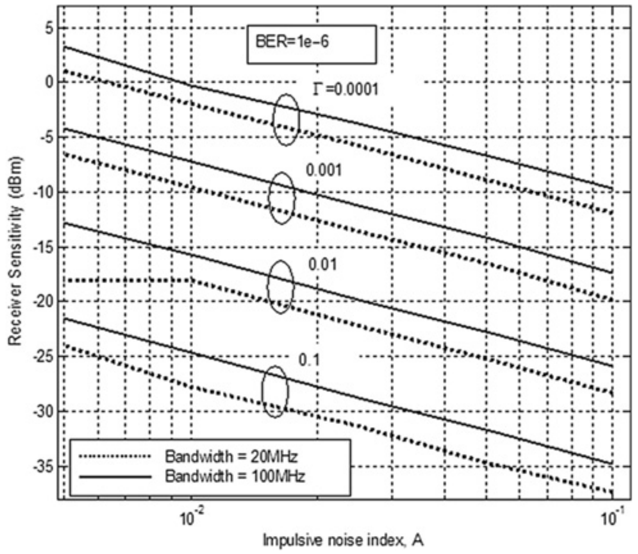

Fig. 6 *Plots of receiver sensitivity against impulsive noise index, A for PLC system with different values Γ (BW = 20 MHz and 100 MHz)*

received power P_s (dBm) are shown in Figs. 5*a–d* for bandwidth of 100 MHz (99.7 MHz) and different values of A and Γ as a parameter. Comparison of the figures with those of 20 MHz bandwidth reveals that that there is further degradation in BER because of higher noise power at 100 MHz bandwidth.

The plots of receiver sensitivity at a BER of 10^{-6} for bandwidths of 20 and 100 MHz are depicted in Fig. 6 as a function of Γ and A as a parameter. The figure clearly reveals the impact of impulsive noise on the performance of a PLC system at a given value of Γ, A and bandwidth. It is found that there are significant penalties in signal power at a given BER at a given value of Γ and A because of impulsive noise. Lower values of A and smaller values of Γ cause higher impulsive noise and hence more power penalty. The plots of power penalty at a BER of 10^{-6} because of combined effect of impulsive noise and background noise are depicted in Fig. 7. The power penalty is computed with respect to $A = 0.1$ which is taken as reference, A_{ref}. The penalty is significant at higher bandwidth and smaller values of A. The values of power penalty range from 0 to 25 dB as A is decreased from 0.1 to 0.0001. However, the power penalty is almost independent of the value of Γ, as the reference value of the receiver sensitivity is taken for $A = 0.1$ and corresponding value of Γ.

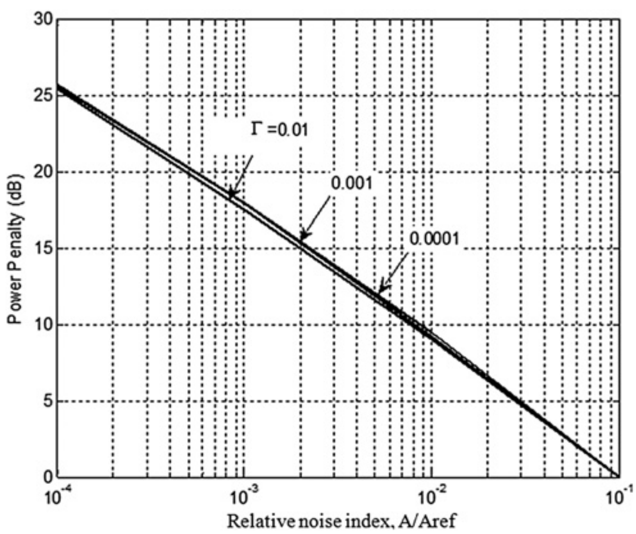

Fig. 7 *Plots of power penalty against impulsive noise index, A/A_{ref} for PLC system with different values Γ (BW = 20 MHz)*

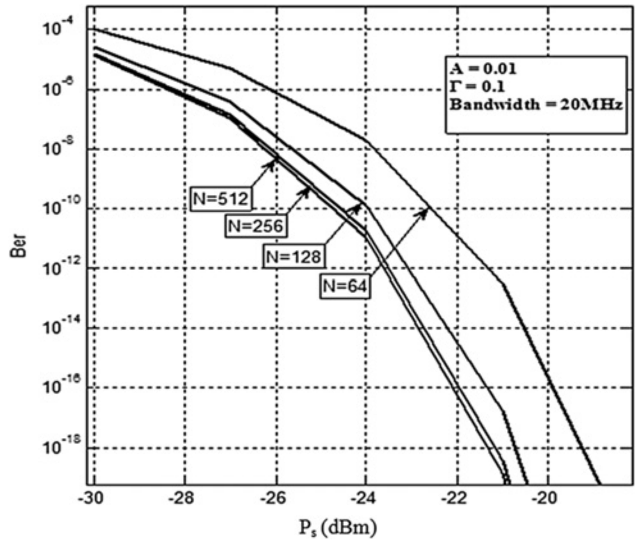

Fig. 8 *Plots of BER against received power, P_s for PLC system with different values N (where A = 0.01, Γ = 0.1, BW = 20 MHz)*

The plots of BER against P_s (dBm) for $A = 0.01$, $\Gamma = 0.1$ and bandwidth, $B = 20$ MHz are shown in Fig. 8 for number of OFDM carriers $N = 64$, 128, 256, 512. It is noted that there are improvements in receiver BER performance with increase in the number of OFDM subcarriers because of less effect of noise at a smaller sub-channel bandwidth. The amount of improvement is about 2–3 dB with N increase from 64 to 512. The plots of receiver sensitivity to achieve a BER of 10^{-6} are depicted in Fig. 9 for $A =$ 0.01, 0.001, 0.0001 and $\Gamma = 0.1$ at a bandwidth of 20 MHz as a function of number of OFDM carriers. It is noted that there are significant effects of impulsive noise at smaller values of A which can be slightly reduced by increasing the number of OFDM subcarriers.

SNR (decibels) against received power, P_s (dBm) are also plotted in Fig. 10 for $R_{\text{in}} = 100\ \Omega$, $\Gamma = 0.001$ and bandwidth, $B = 20$ MHz. It

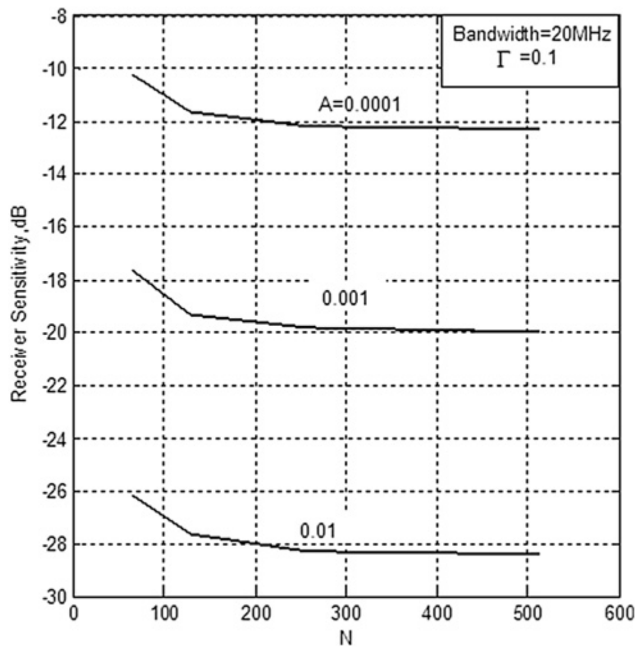

Fig. 9 *Plots of receiver sensitivity against N for PLC system with different values A (where Γ = 0.1, BW = 20 MHz)*

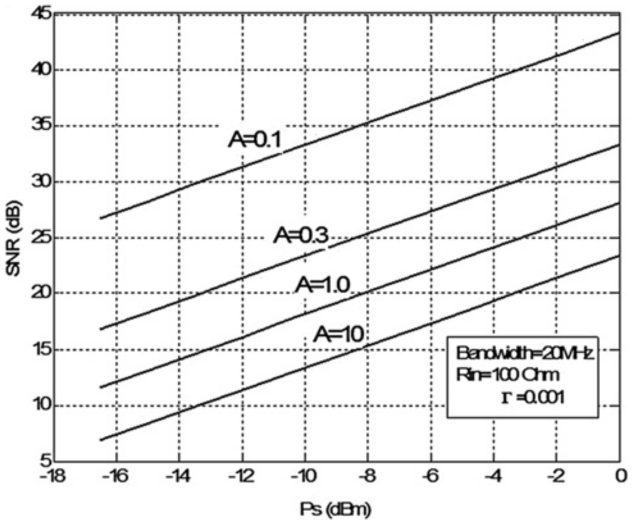

Fig. 10 *Plots of SNR against received error power, Ps for PLC system with different values of A*

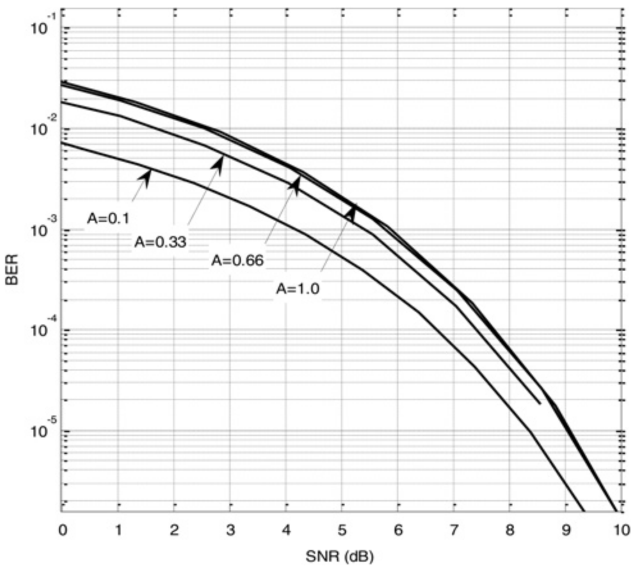

Fig. 11 *Plots of SNR against bit rate, BER for PLC system with different values of A*

is noted that the SNR changes linearly with received power and is higher at smaller values of impulsive noise index A. Furthermore, to compare our analytical results with simulation results reported in [18]. We present the BER as a function of SNR (dB) in Fig. 11 for various values of A with same parameters of SISO PL communication system as in [18] including the background PL noise and impulsive noise. It is noted that BER values obtained by our analytical computation conforms well with the simulation results of [18] for same system parameters with little difference in BER values. The difference may be because of non-flat noise spectral density for background noise considered in our analytical model, whereas the noise spectral density considered for simulation is flat with two-sided PSD $N_0/2$ (W/Hz).

5 Conclusion

An analytical approach is developed to evaluate the BER performance of an OFDM PL communication system taking into account the combined influence of background PL noise and impulsive noise which is modelled by Middleton class-A noise model. The effect of both background noise and impulsive noise on BER performance is numerically evaluated for several system and noise parameters. It is found that there is significant power penalty because of impulsive noise of the order of 0–25 dB depending on the value of impulsive noise index at a BER = 10^{-6}. The penalty can be slightly reduced by increasing the OFDM carriers. The analytical approach will be useful to evaluate the performance of PLC system with coding and diversity.

6 References

[1] Tachikawa S., Hokari H., Marubayashi G.: 'Power line data transmission'. IEICE Technical report, SSTA89-7, March 1989

[2] Chan M.H.L., Donaldson R.W.: 'Amplitude, width, and interarrival distributions for noise impulses on intrabuilding power line communication networks', *IEEE Trans. Electromagn. Compat.*, 1989, **31**, (3), pp. 320–323

[3] Lampe L.H.-J., Hubber J.B.: 'Bandwidth efficient power line communications based on OFDM', *Int. J. Electron.*, 1999, **54**, pp. 200–210

[4] Katayama M.: 'Introduction to robust, reliable and high-speed power-line communication systems', *IEICE Trans. Fundam.*, 2001, **E84-A**, (12), pp. 2958–2965

[5] Zimmermann M., Dostert K.: 'Analysis and modeling of impulsive noise in broad-band powerline communications', *IEEE Trans. Electromagn. Compat.*, 2002, **EMC-44**, (1), pp. 249–258

[6] Zimmerman M., Dostert K.: 'A multipath model for the powerline channel', *IEEE Trans. Commun.*, 2002, **50**, (4), pp. 553–559

[7] Middleton D.: 'Statistical-physical model of electromagnetic interference', *IEEE Trans. Electromagn. Compat.*, 1977, **EMC-19**, (3), pp. 106–126

[8] Zimmermann M., Dostert K.: 'An analysis of broadband noise scenario in powerline networks'. ISPLC 2000, Guia de Projecto Electro de Centrais Eolicas, 2003, vol. 1

[9] Gotz M., Rapp M., Dostert K.: 'Power line characteristics and their effect on communication system design'. IEEE Communication Magazine, April 2004

[10] Meng H., Guanand Y.L., Cheng S.: 'Modeling and analysis of noise effects on broadband power line communications', *IEEE Trans. Power Deliv.*, 2005, **20**, (2), pp. 630–637

[11] Hormis R., Berenguer I., Wang X.: 'A simple baseband transmission scheme for power line channels', *IEEE J. Sel. Areas Commun.*, 2006, **24**, (7), pp. 1351–1363

[12] Cataliotti A., Daidone A., Tine G.: 'Power line communication in medium voltage systems: characterization of MV cables', *IEEE Trans. Power Deliv.*, 2008, **23**, (4), pp. 1896–1902

[13] Andreadou N., Nivoi Pavlidou F.: 'PLC hannel: impulsive noise modeling and its performance evaluation under different array coding schemes', *IEEE Trans. Power Deliv.*, 2009, **24**, (2), pp. 585–595

[14] Bhatti S.A., Shan Q., Glover I.A., *ET AL.*: 'Impulsive noise modeling and prediction of its impact on the performance of WLAN receiver'. 17th European Signal Processing Conf. (EUSIPCO 2009), August 2009

[15] Cortés J.A., Diez L., Cañete F.J., Martinez J.J.S.: 'Analysis of the indoor broadband power-line noise scenario', *IEEE Trans. Electromagn. Compat.*, 2010, **52**, (4), pp. 849–858

[16] Nassar M., Lin J., Mortazavi Y., Dabak A., Kim H., Evans B.L.: 'Local utility powerline communications in the 3–500 kHz band: channel impairments, noise, and standards', *IEEE Signal Process. Mag. 1*, 20 January 2012, **29**, pp. 116–127

[17] Kim Y.H., Hoe Kim K., Myoung Oh H., Ho Kim Cheol Kim K.: 'Mitigation of effect of impulsive noise for OFDM systems over power line channels'. IEEE Int. Symp. on Powerline Communication and its Application, ISPL – 2008, April 2008

[18] Yoo J., Choe S.: 'MIMO-OFDM based broadband power line communication using antenna and fading diversity'. ENERGY 2012: The Second Int. Conf. on Smart Gird, Green Communication and IT Energy-aware Technologies, May, 2012

[19] Rahman M.M., Majumder S.P.: 'Analysis of a powerline communication system over a non-white additive Gaussian noise channel and performance improvement using diversity reception', *Netw. Commun. Technol. J.*, 2012, **1**, (1), pp. 333–343

[20] Hu X., Chen Z., Yin F.: 'Impulsive noise cancellation for MIMO power line communications', *J. Commun.*, 2014, **9**, (3)

[21] Rahman M.M., Majumder S.P.: 'Performance analysis of a OFDM SISO powerline communication system with non-white Gaussian channel noise'. IEEE First Int. Conf. on Electrical Engineering and ICT (ICEEICT 2014), MIST, Dhaka, 10–12 April 2014 (to appear in IEEE explore)