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Performance Assessment of Cooperative Relaying in Power Line Communication System

B.A. Ojo[1] and P. O. Aiyelabowo[1]
[1]*Department of Electrical/ Electronics Engineering, The Federal Polytechnic,Ilaro,Ogun State, Nigeria.*

ABSRACT: *The cost incurred on installation for broadband data for consumer has made the power line communication the technology to be considered for the provision. As appropriate as this medium is, the challenges inherent in it makes high-speed transmission unreliable, as signal propagated through it suffers attenuation, experiences multipath and bewitchment of noise. This causes depreciation of the signal as it traverses the medium (power line). This paper considers cooperative relaying for the improvement of PLC reliability. It deploys cooperative transmission protocols, amplify-and-forwad and decode-and-forward. Three links were investigated for symbol error rate and outage probability. These links are amplify-and-forward cooperative link, decode-and-forward cooperative link and non-cooperative link (PLC conventional). The cooperative links achieved reduction in symbol error rate and outage probability, with th decode-and-forward having the best performance.*

Keywords: *Amplify-and-forward, decode-and-forward, outage probability, relay cooperation and symbol error rate.*

I. INTRODUCTION

Implementation of the electric power line for broadband transmission has gained tremendous emphasis and cross examination. Thus, the power network which has vast deployment is considered for the provision of data (broadband) for various types of application. The ubiquitous characteristic of this medium (power line network) presents it as a choice for deployment of broadband.

Therefore, communication signal is transformed with a form that will be enhanced for transmission over power line network. Power line communication (PLC) is the technology that conveys data over the power line network, intended for the provision of power supply, hence new installation is not required for communication services. The basic PLC network required for this process includes, PLC Base station and PLC modem. The PLC modem connects the subscriber communication equipment to the power line. This is done by using specific coupling techniques for receiving and sending data on the medium. This provides the function of physical\data –link layer and that of logic link control. The nature and characteristic of the power line network, poses a number of challenges to its usage for data transmission.

This nature includes.

(i) Tree topology
(ii) Time variance
(iii) Length ofthe network.

The challenges posed by this medium to the high speed data is also due to the fact that the medium was not intended for data transmission at design. Hence, the power network is bewitched with the challenges of attenuation, owing to length of cable and branches, noise (Gaussian and impulsive), owing to load connections to the line and multipath, which are caused by line mismatch, that is, the load connected at far end does not match with lines characteristic impedance.Thus, the power line network is a medium besieged with many impediments to signal transmission. To combat these challenges, the orthogonal frequency division multiplexing (OFDM), having an advantage of robust response to muthipath,selative fading and different kinds of interference, is the modulation scheme implemented. The OFDM only reduces slightly the effects of these challenges. Several activities were deployed in recent times to mitigate these challenges so as to present the PLC as the Technology for smart grid system. These activities include implementation of MIMO technique in PLC, the improvement achieved is with cross talk as trade off. Repeaters were also implemented, this resulted in further cost. In this paper, the power line cooperative communication (PLCC) system is presented. Its reliability in the face of all the power line network impediments was investigated. Amplify-and-forward and Decode-and-forward cooperative transmission protocols were deployed. Two performance metric symbol error rate and outage probability were examined for PLC and PLCC system. The PLCC yielded an improvement in SER and outage probability over the conventional PLC system.

II. SYSTEM MODEL

The power line cooperative communication system is as represented in a schematic diagram shown in Fig. 1. It consists of basically three components connected on the power line network as the transmission medium. These components are, the source modem, relay modem and destination modem. The system model for the scheme shown in Fig. 2 is presented in Fig. 3. The PLC base station makes up the source modem, it is the source of the message to be transmitted, and depicted as an OFDM transmitter succeeded by a noise mitigation system. The relay is both an OFDM receiver and transmitter with noise mitigation, while the destination modem is represented as an OFDM receiver. Each of these propagates its signal through the power line channel. The relay modem passes its received signal through cooperation process, this is called cooperative transmission protocol (CTP), before it is transmitted to the destination modem.

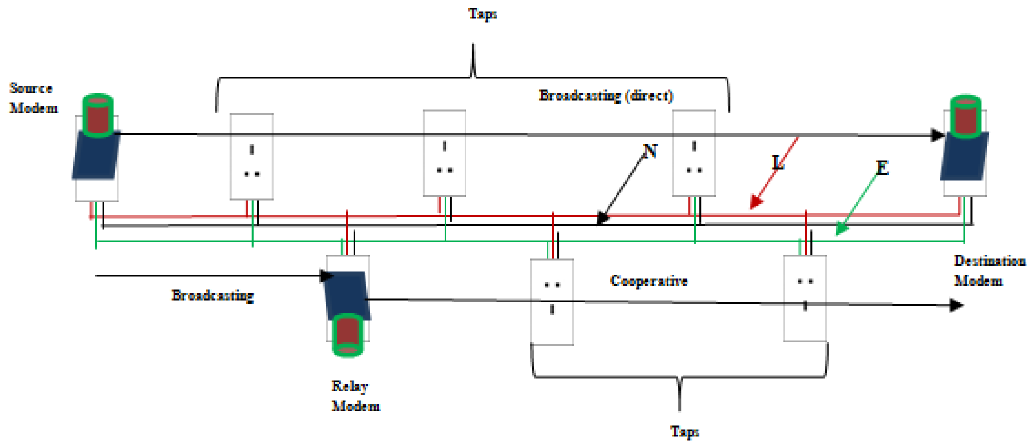

Figure 1: Power line cooperative communication scenario

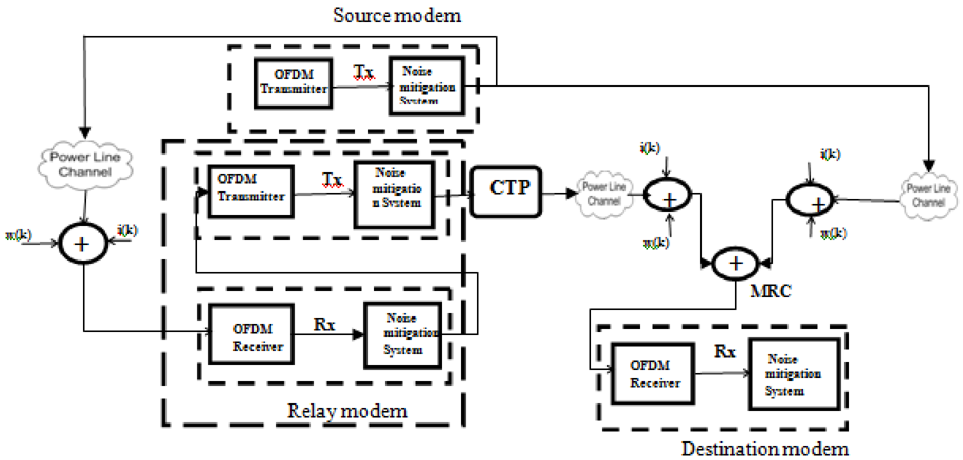

Figure 2: Cooperative power line communication system model

Two cooperative protocol were deployed in the system, amplify-and-forward and decode-and-forward. The system model structure can be categorized into cooperative section and noise mitigation section respectively.

III. PLC CHANNEL AND NOISE DESCRIPTION

Philip's echo model and Zimmermann &Dostert model [1], [2] are the most prominent model approach adopted for power line channel. The channel response, represented as transfer function for the channel is shown in (1);

$$H(f) = \sum_{i=1}^{N} g_i \cdot e^{-\left(\alpha_o + \alpha_1 f^k\right) \cdot d_i} \cdot e^{-j2\pi f \frac{d_i}{v_p}} \quad (1)$$

Where, g_i is a factor used for describing weight of the individual's path, *d is the length of the path,* α_1 is increase of attenuation, α_o is offset attenuation, and k is exponent of attenuation. N defines the number of taps (branches) of the line being considered.

The noise in PLC is quite different from the noise characteristic in other conventional communication systems. It combines both impulsive and Gaussian noise. The channel is bewitched by five categories of noise, which includes; coloured background noise, Narrow-band noise, Periodic Impulsive Noise Asynchronous to the Mains Frequency, Periodic Impulsive Noise Synchronous to the Mains Frequency and Asynchronous impulsive noise. The first three are classified as White Additive Gaussian Noise (AWGN) while the last are considered as impulsive, they are time –varying. This impulsive noise is modelled using Middleton's class A noise model, represented as [3];

$$i_k = b_k g_k \quad (2)$$

Where b_k is the Poisson process designating the arrival of impulsive noise and g_k is the white Gaussian process with zero mean and variance, σ_W^2.

Impulsive noise are transient characterized uniformly distributed disturbances over the useful transmission system pass band. They can be caused by voltage spikes in equipment, voltage changes on adjacent pairs in a copper cable, tones generated for network signalling, maintenance and test procedures, lightning flashes during thunderstorms, and a wide variety of other phenomena.

IV. NOISE MITIGATION MODEL

The system used to mitigate the noise in the PLCC proposed system is shown in Fig. 4. The noise inherent on the power line is mitigated on both the transmitter and the receiver sections. The signal to be transmitted is passed through two series of encoding; Reed-Solomon encoding and convolutional encoding at different code rates. The encoded bits were interleaved using random interleaver to achieve a combat against the busty impulsive noise in the power line channel. Mapping was then done using QAM before modulation using inverse discrete Fourier transform (IDFT). In the receiver the opposite of the processes in the transmitter is carried out, namely; demodulation by means of discrete Fourier transform (DFT), demapping (both PSK and QAM), de-interleaving, Viterbi decoding and RS decoding. The RS encoding is robust for impulsive noise mitigation while the convolutional encoding combats well the AWGN.

Note that the place of publication, publisher, and year of publication are enclosed in brackets. Editor of book is listed before book title.

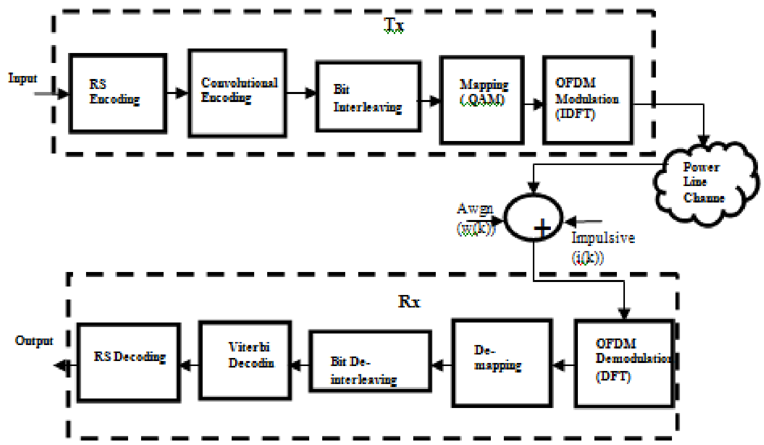

Figure 3: Noise Mitigation System model

V. COOPERATION MODEL

Just as in cooperative activity in wireless systems, the source and the relay node transmits P_1 and P_2 powers respectively at both transmissions scenarios. The two transmission scenarios are broadcasting (direct) and cooperative as depicted in Fig. 1.

During the first transmission (broadcasting) with an OFDM of symbol length, N, and cyclic prefix (CP) of length $l_{cp} \geq \max\left(l_{sd}, l_{sr}, l_{rd}\right)$, the received signals at both the PLC destination and relay nodes is as shown in Eqs. (3) & (4), while (5) describes the noise components.

$$y_{sr}^{pl} = \sqrt{\frac{P_1}{N}} h_{sr}^{pl} x + n_{sr}^{pl} \quad (3)$$

$$y_{sd}^{pl} = \sqrt{\frac{P_1}{N}} h_{sd}^{pl} x + n_{sd}^{pl} \quad (4)$$

$$n_{sr}^{pl} = w_{sr} + i_{sr} \text{ and } n_{sd}^{pl} = w_{sd} + i_{sd} \text{ [4]} \quad (5)$$

In the cooperative transmission, the PLC relay modem processes the received signal as prescribed by the adopted cooperative protocol, then forwards it through its channel to the PLC destination nodes. The signal received at the destination node at this second transmission is given as

$$y_{rd}^{pl} = \sqrt{\frac{P_2}{N}} h_{rd}^{pl} q\left(y_{sr}^{pl}\right) + n_{rd}^{pl} \quad (6)$$

$$n_{rd}^{pl} = w_{rd} + i_{rd} \quad (7)$$

P_2 is the transmitted power at the PLC relay node and q represents the cooperative protocol deployed.

$$\text{Let } \sqrt{\frac{P_1}{N}} = \sqrt{P_1'} \text{ and } \sqrt{\frac{P_2}{N}} = \sqrt{P_2'} \quad (8)$$

PLC Amplify-and Forward Cooperation

This process in the PLC is similar to the one described in wireless communication system, except for the channel and the inherent noise. The signal received at both the destination and the relay nodes in the broadcasting phase is as described in equations (11) and (12). The relay received signal is made stronger by a factor β^{pl} [5]

$$\beta^{pl} = \frac{\sqrt{P_2'}}{\sqrt{P_1' \left|h_{sr}^{pl}\right|^2 + N_x}} \quad (9)$$

$$N_x = N_w + N_i \quad (10)$$

$$10\log_{10} N_w = N_0 + N_1 . e^{-\frac{f}{f_1}} \left(\mathrm{dBmW/Hz}\right)$$

The amplified signal is then transmitted to destination in the second transmission phase (cooperative). The signal received at the destination during this transmission will be;

$$y_{rd}^{pl} = \beta^{pl} h_{rd}^{pl} y_{sr}^{pl} + n_{rd}^{pl} \text{ and } n_{rd}^{pl} = w_{rd} + i_{rd} \quad (11)$$

The output of the system at the destination having applied amplify-and-forward is given in (12)

$$Y_{out}^{AF} = y_{sr}^{pl} + y_{rd}^{pl} = \sqrt{P_1'} h_{sr}^{pl} x + n_{sr}^{pl} + \frac{\sqrt{P_1' P_2'}}{\sqrt{P_1' \left|h_{sr}^{pl}\right|^2 + N_x}} h_{rd}^{pl} h_{sr}^{pl} x + \frac{\sqrt{P_2'}}{\sqrt{P_1' \left|h_{sr}^{pl}\right|^2 + N_x}} h_{rd}^{pl} n_{sr}^{pl} + n_{rd}^{pl} \quad (12)$$

PLC Decode and Forward Cooperation

In this protocol as described in section 6, the relay modem decodes and re-encodes the signal received. Its channel and noise are as described in PLC amplify and forward. After decoding and encoding at the PLC relay node, the signal is re-transmitted to the destination through the channel with coefficient h_{rd}^{pl} . The signal received at the destination will be given as

$$y_{rd}^{pl} = \sqrt{\beta_2^{pl}}\, h_{rd}^{pl} x + n_{rd}^{pl} \tag{13}$$

Where $\beta_2^{pl} = P_2'$ if relay correctly decodes the transmitted signal and $\beta_2^{pl} = 0$ if otherwise.

The output at the destination for decode and forward for correct decoding, is as represented in (14)

$$Y_{out}^{DF} = \sqrt{P_1'}\, h_{sr}^{pl} x + n_{sr}^{pl} + \sqrt{P_2'}\, h_{rd}^{pl} x + n_{rd}^{pl} \tag{14}$$

Since the noise characteristics of the channels are same, it is assumed that,

$n_{sd}^{pl} = n_{sr}^{pl} = n_{rd}^{pl}$ and the noise PSD's of the channels are also same,

The signals were combined at the destination using the *Maximum Ratio Combining (MRC).* The signal combination at the destination for both cooperative protocols are given in (13) and (14);

$$Y_{out}^{MRCAF} = \left(\sqrt{P_1'} \left|h_{sd}^{pl}\right|^2 + \frac{\sqrt{P_1' P_2'}}{\sqrt{P_1' \left|h_{sr}^{pl}\right|^2 + N_x}} \left|h_{rd}^{pl}\right|^2 \left|h_{sr}^{pl}\right|^2 \right) x + \left(h_{sd}^{pl} n_{sd}^{pl} + \frac{\sqrt{P_2'}}{\sqrt{P_1' \left|h_{sr}^{pl}\right|^2 + N_x}} h_{rd}^{pl} n_{sr}^{pl} + h_{rd}^{pl} n_{rd}^{pl} \right) \tag{15}$$

$$Y_{out}^{MRCDF} = \left(\sqrt{P_1'} \left|h_{sd}^{pl}\right|^2 + \sqrt{P_2'} \left|h_{rd}^{pl}\right|^2 \right) x + \left(\left|h_{sd}^{pl}\right|^2 n_{sd}^{pl} + \left|h_{rd}^{pl}\right|^2 n_{rd}^{pl} \right) \tag{16}$$

The resultant SNR in all the subcarriers for amplify-and-forward protocol can be estimated by

$$\lambda_{AF}^{pl} = \frac{A^2}{B} \tag{17}$$

$$A = \left(\sqrt{P_1'} \left|h_{sd}^{pl}\right|^2 + \frac{\sqrt{P_1' P_2'}}{\sqrt{P_1' \left|h_{sr}^{pl}\right|^2 + N_x}} \left|h_{rd}^{pl}\right|^2 \left|h_{sr}^{pl}\right|^2 \right)$$

While for the decode-and-forward, SNR for all subcarriers is described by

$$\lambda_{DF}^{pl} = \frac{\left(\sqrt{P_1'} \left|h_{sd}^{pl}\right|^2 + \sqrt{P_2'} \left|h_{rd}^{pl}\right|^2 \right)^2}{\left(\left|h_{sd}^{pl}\right|^2 + \left|h_{rd}^{pl}\right|^2 \right)} \tag{18}$$

$$\lambda_D^{pl} = \frac{\sqrt{P_1'} \left|h_{sd}^{pl}\right|^2}{N_x} \tag{19}$$

VI. SYMBOL ERROR ANALYSIS

For Amplify-and-forward SER analysis, the SER is formulated according to [6], when the received SNR at the destination with QAM modulation, as;

$$\chi_{AF} = \left[\frac{4K}{\pi} \int_0^{\pi/2} - \frac{4K^2}{\pi} \int_0^{\pi/4} \right] \frac{1}{1 + \frac{b_{QAM}}{2\beta_0 \sin^2\theta}} \left\{ \frac{(\beta_1 - \beta_2)^2 + (\beta_1 + \beta_2) \frac{b_{QAM}}{2\sin^2\theta}}{\Delta^2} + \frac{\beta_1 \beta_2 b_{QAM}}{\Delta^3 \sin^2\theta} \mathrm{In} \left(\frac{\beta_1 + \beta_2 + \frac{b_{QAM}}{2\sin^2\theta} + \Delta}{4\beta_1\beta_2} \right)^2 \right\} d\theta \tag{20}$$

where $\beta_0 = N_x / P_1^{'} \left| h_{sd}^{pl} \right|^2$, $\beta_1 = N_x / P_1^{'} \left| h_{sr}^{pl} \right|^2$, $\beta_2 = N_x / P_2^{'} \left| h_{rd}^{pl} \right|^2$, and $\Delta^2 = (\beta_1 - \beta_2)^2 + 2(\beta_1 + \beta_2)s + s^2$, while $s = b_{QAM} / (2\sin^2\theta)$. Other terms are defined as, $K = 1 - \frac{1}{\sqrt{M}}$, $b_{QAM} = 3/(M-1)$ and $Q(u) = \frac{1}{2\pi}\int_u^\infty \exp(-\frac{t^2}{2})dt$.

In the decode-and-forward protocol, the relay can either decode the source signal correctly or incorrectly. At these instances, during the cooperation phase the relay power $P_2^{'} = P_2^{'}$ for correct decoding and $P_2 = 0$ otherwise. The SER is formulated as [6]

$$\chi_{DF} = F_2\left(1 + \frac{b_{QAM} P_1^{'} \left|h_{sd}^{pl}\right|^2}{2N_x \sin^2\theta}\right) F_2\left(1 + \frac{b_{QAM} P_1^{'} \left|h_{sr}^{pl}\right|^2}{2N_x \sin^2\theta}\right) + F_2\left(\left(1 + \frac{b_{QAM} P_1^{'} \left|h_{sd}^{pl}\right|^2}{2N_x \sin^2\theta}\right) F_2\left(1 + \frac{b_{QAM} P_2^{'} \left|h_{sr}^{pl}\right|^2}{2N_x \sin^2\theta}\right)\right) \times \left[1 - F_2\left(1 + \frac{b_{QAM} P_1^{'} \left|h_{sr}^{pl}\right|^2}{2N_x \sin^2\theta}\right)\right] \quad (21)$$

Where

, $N_x = N_w + N_i$, N_w and N_i are Gaussian and impulsive noise PSD's respectively.

For direct link, the SER was formulated as,

$$\chi_D = F_2\left(1 + \frac{b_{QAM} P_1 \left|h_{sd}^{pl}\right|^2}{2N_x \sin^2\theta}\right) \quad (22)$$

F_2 is as defined in previous case.

VII. OUTAGE PROBABILITY ANALYSIS

Outage probability is defined as the probability that the instantaneous error rate exceeds a specified value or equivalently that the (instantaneous) combined signal-to-noise ratio (SNR), falls below a certain specified threshold, [7] i.e.

$$P_{out} = P[0 \le \lambda_t \le \lambda_{th}] = \int_0^{\lambda_{th}} P_{\lambda_t}(\lambda_t) d\lambda_t \quad (23)$$

where $P_{\lambda_t}(\lambda_t)$ is the probability density function (pdf) of λ_t.

Therefore, cumulative distribution function (cdf) of λ_t obtained at λ_{th} is P_{out}. An approach to finding the outage probability, according to [8], is to first find the pdf of λ_t and then integrate over that pdf as in (23).

Therefore, the whole communication system is in outage state when the maximum average mutual information, $I_D < R$, where R is the spectral efficiency. In information theory, I_D depends on the instantaneous SNR, λ_u^{pl} $(u \in AF, DF, D)$, of the MRC combined *signal at the destination.* The outage probability of the source node is

$$P_{out} = \Pr\{\lambda_u^{pl} < \lambda_{th}^{pl}\}, \ (u \in AF, DF, D)$$

where λ_{th}^{pl} is the threshold decided by *R.*

The outage probability for the amplify-and-forward link can be derived using [9] as

$$P_{out\_AF} = \Pr\{\lambda_{AF}^{pl} < \lambda_{th}^{pl}\} = \Pr\{\lambda_{AF}^{pl} < \lambda_{th\_AF}^{pl}\}$$

$$= \int_0^{\lambda_{th\_AF}^{pl}} P_{\lambda_{AF}^{pl}}(\lambda_1) \int_0^{\lambda_{th\_AF}^{pl} - \lambda_1} P_{\lambda_{sd}^{pl}}(\lambda_2) d\lambda_2 d\lambda_1 \quad (24)$$

$$= \int_0^{\lambda_{th\_AF}^{pl}} P_{\lambda_{AF}^{pl}}(\lambda_1) P_{\lambda_{sd}^{pl}}(\lambda_{th\_AF}^{pl} - \lambda_1) d\lambda_1$$

where $P_{\lambda_{AF}^{pl}}(c)$ represents the PDF of the amplify-and-forward path SNR described in Eq. (23).

The outage probability for the decode-and-forward cooperation is described as

$$P_{out\_DF} = \Pr\{\lambda_{DF}^{pl} < \lambda_{th}^{pl}\} = \Pr\{\lambda_{DF}^{pl} < \lambda_{th\_DF}^{pl}\}$$

$$= P_{\lambda_{sr}^{pl}}(\lambda_{th\_DF}^{pl}) + [1 - P_{\lambda_{sr}^{pl}}(\lambda_{th\_DF}^{pl})] \times \int_0^{\lambda_{th\_DF}^{pl}} P_{\lambda_{sd}^{pl}}(\lambda_1) \int_0^{\lambda_{th\_DF}^{pl} - \lambda_1} P_{\lambda_{rd}^{pl}}(\lambda_2) d\lambda_2 d\lambda_1$$

$$= P_{\lambda_{sr}^{pl}}(\lambda_{th\_DF}^{pl}) + [1 - P_{\lambda_{sr}^{pl}}(\lambda_{th\_DF}^{pl})] \times \int_0^{\lambda_{th\_DF}^{pl}} P_{\lambda_{sd}^{pl}}(\lambda_1) P_{\lambda_{rd}^{pl}}(\lambda_{th\_DF}^{pl} - \lambda_1) d\lambda_1 \quad (25)$$

In the case of the direct link, the outage probability is described as

$$P_{out\_D} = \Pr\{\lambda_D^{pl} < \lambda_{th}^{pl}\} = \Pr\{\lambda_D^{pl} < \lambda_{th\_D}^{pl}\}$$

$$= \int_0^{\lambda_{th\_D}^{pl}} P_{\lambda_{sd}^{pl}}(\lambda_1) d\lambda_1 \quad (26)$$

The spectral efficiency was set at $R = 1$ *b/s/Hz*, while the threshold SNR is $\lambda_{th}^{pl} = \lambda_{th\_AF}^{pl} = \lambda_{th\_DF}^{pl} = \lambda_{th\_D}^{pl} = 2^{2R} - 1$. The power of 2 is for the bi transmission scheme of the system.

VIII. SIMULATION

The system model shown in Fig. 2 was simulated for the study of the systems' BER performance. The power line channel was simulated following (1). *N*, number of taps was fixed at 8, $a_0 = 0$, $a_1 = 1.6\text{x}10^{-10}$ and $k = 1$. Other parameters, d_i and g_i were generated randomly following the number of taps and the length of the line (20 m). As stated earlier, noise in PLC is a combination of AWGN and impulsive noise, hence the impulsive noise simulated is a high one.

Reed-Solomon encoding was done at $n = 64$ and $k = 48$. The convolutional code rates of ½ was implemented for a 16-QAM modulation scheme. The generator polynomials (10101011, 10000101) was implemented in the encoder with a constraints of $k = 8$. The duo of the transmitter and the receiver uses 256 subcarriers to perform IFFT and FFT respectively with an OFDM symbol of 10. A cyclic prefix of 64 was inserted. The OFDM signal was passed through the power line channel described by the channel response in (1) over a frequency of 0-30 MHz. The OFDM in the receiver is demodulated by DFT, demapped respectively (QAM) and de-interleaved. After de-interleaving, the signal was Viterbi decoded at different traceback depths of 4k = 32. $P_1 = {}^{P}\!/_{2}$ was used for the broadcasting phase while the other half is used for the cooperation phase, hence, $P = P_1 + P_2$. In conformity with electromagnetic compatibility requirement, *P* was chosen for 12.5 *dBmW*over 0 – 30 MHz frequency band. OFDM parameters as in the noise mitigation simulation were maintained. The noise PSD, N_x, a sum of AWGN and impulsive noises were appropriately defined using Eqs. (10) and (11), $N_o = -125$, $N_1 = 35$ and $f_1 = 3.6$.

For the symbol error rate analysis simulation, M was set at 16 (2^4) for QAM-16 modulation scheme deployed. The symbol error rate formulations, Eqs. (20), (21) and (22) were simulated for performance of the three links for the three relay location scenario. The result is as presented on Fig.4. The SER for all the links at different relay location, for 100 symbols transmission. The cooperative links, amplify-and-forward and decode-and-forward presents an exceptional performance in contrast to the direct link. For this transmission at 6 dB SNR, 11 symbols are in error for direct link (conventional PLC link), while for the cooperative links, no symbol is in error.

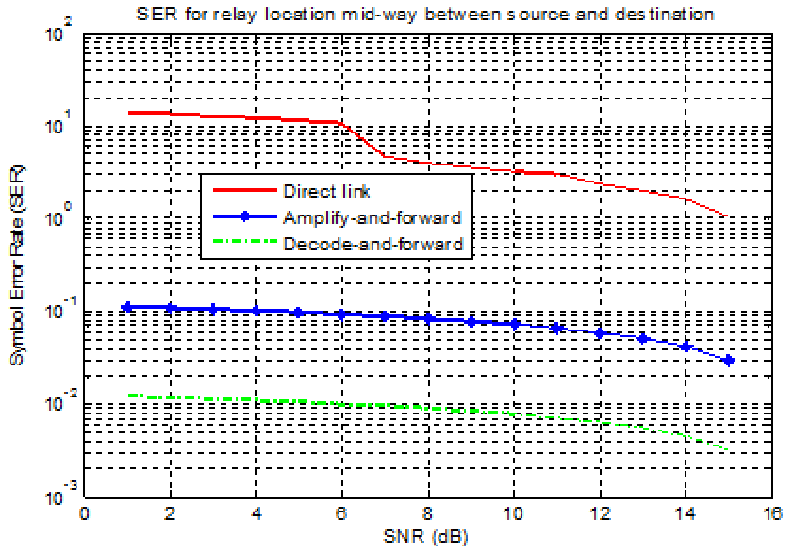

Figure 4: Symbol error rate performance

The outage probability formulations for the three links (AF, DF and D), using (23), (24),(25) and (26), were simulated for performance investigation.

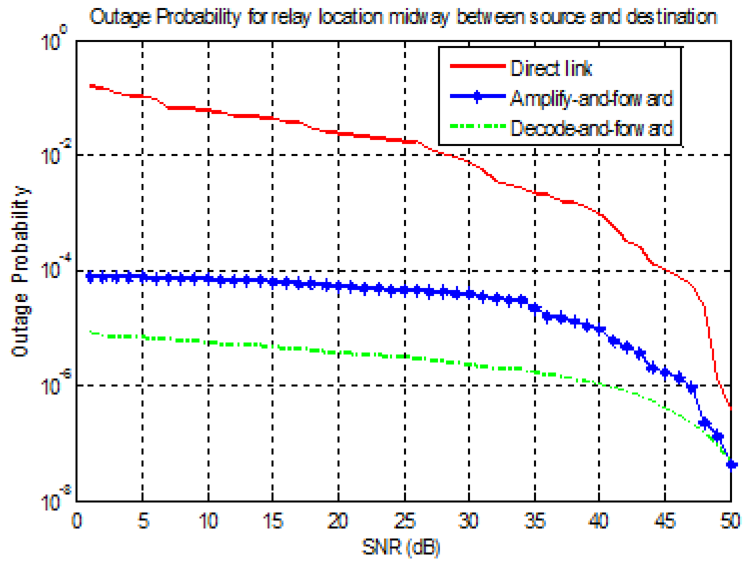

Figure 5: Symbol error rate performance

The cooperative links, amplify-and-forward and decode-and-forward presents an outstanding performance in contrast to the direct link. The performances of both cooperative protocols are close owing to the mitigation system incorporated. At 5 dB SNR, the probability of outage on the PLC direct link (c0nventional PLC link) is 10.4 %, while for amplify-and-forward and decode-and-forward are 0.007 % and 0.0005 % respectively.

IX. CONCLUSION

In this paper, a technique deployed to achieve reliability in the power line communication (PLC) system is presented. The technique is a, modem (relay) cooperating with the source modem for signal transmission to the destination. The key contribution is in the system reliability achieved, for which system's outage probability and symbol error rate were parameters investigated. Two cooperative channels, amplify-and-forward and the decode-and-forward, along with the direct channel (without cooperation), were examined for those parameters mentioned. The cooperative links were seen to attain outstanding reliability over the direct link. The noise mitigation system incorporated contributed enormously to the drastic reduction in the systems symbol error rate and outage probabilities of both cooperative links, achieving performances that are close.

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