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Performance of Optimal Power Allocation Algorithm on Selective Cooperative Broadband over Powerline System

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Abstract: *Broadband on power line technology is one that implements the existing power line network as a medium for the deployment of broadband data. Hence, broadband over powerline has the potential of meeting the demand of broadband for various applications because of the ubiquitous nature of the power line network, which is its medium. But as potent as the technology is, signals propagated along the powerline suffers so much impediment. The network introduces both impulsive and awgn noise and attenuates the signal severely. Implementing selective cooperative relaying with equal power allocation has been deployed on broadband over power line, it achieved some level of performance improvement. The two transmission links, direct and cooperative, were allocated equal power for the transmissions. In this paper, optimal power scheme for best performance was determined. This optimal scheme was implemented for the two transmission links in the selective algorithm. A ratio of* $\frac{1}{3}P_t : \frac{2}{3}P_t$ *(direct: cooperative) was achieved for the best performance. The performance evaluation was carried out for symbol error rate and channel capacity. This performance was benchmarked with those of equal power allocation selective scheme. The optimal power scheme achieved a prominent improvement in both channel capacity and symbol error rate.*

Keywords*: Direct-link, cooperative link, equal-power, optimal-power, channel capacity and symbol error rate.*

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I. Introduction

Modern society requirement of reliable and efficient widely distributed and automated energy delivery network is achieved in the smart grid (SG), a system that makes use of its two-way information flow and electricity, to achieve this fit. Information exchange in SG is achieved by data communication technology. Data communication requirements of reliability, broad coverage, quality of service support and a privacy and security that is guaranteed are ensured in SG applications.

Broadband over powerline (power line communication) amongst several communication architectures, offers the SG the advantages of cost effectiveness and broadband coverage. It is a technology that utilizes the existing power infrastructure to provide electric power and transmit information alongside. Thus, anywhere power exists can be provided with communication.

Applications of voice, video, multimedia, internet and home-networking have been provided via the PLC technology. This technology can play a vital role in the future of SG.

Direct link communication in the PLC has limited channel capacity and transmission distance, owing to the characteristics of the medium, which does not support data transmission because it was not designed for communication purposes but for power distribution. Severe signal attenuation, as the high-frequency signal traverses the long distance medium is responsible for the limited channel capacity. The complexity of the noise on the power line, consisting of several components, is another source of signal degradation characteristic. Noise in PLC is composed of five (5) different types of components, which can be summed into white additive Gaussian noise (AWGN) and impulsive noise. Furthermore, the transmit power restriction policy which is regulated by electromagnetic compatibility (EMC) policy, also contributes to channel's limited capacity. Thus, the reliability of the PLC direct link is bewitched by the aforementioned challenges, rendering the channel (direct link) unreliable.

The suitability and economic advantage of the PLC for SG system and the inherent degradation characteristic of the medium due to its nature, has spurned up research towards enhancing the channel capacity and widening the coverage area of the system.

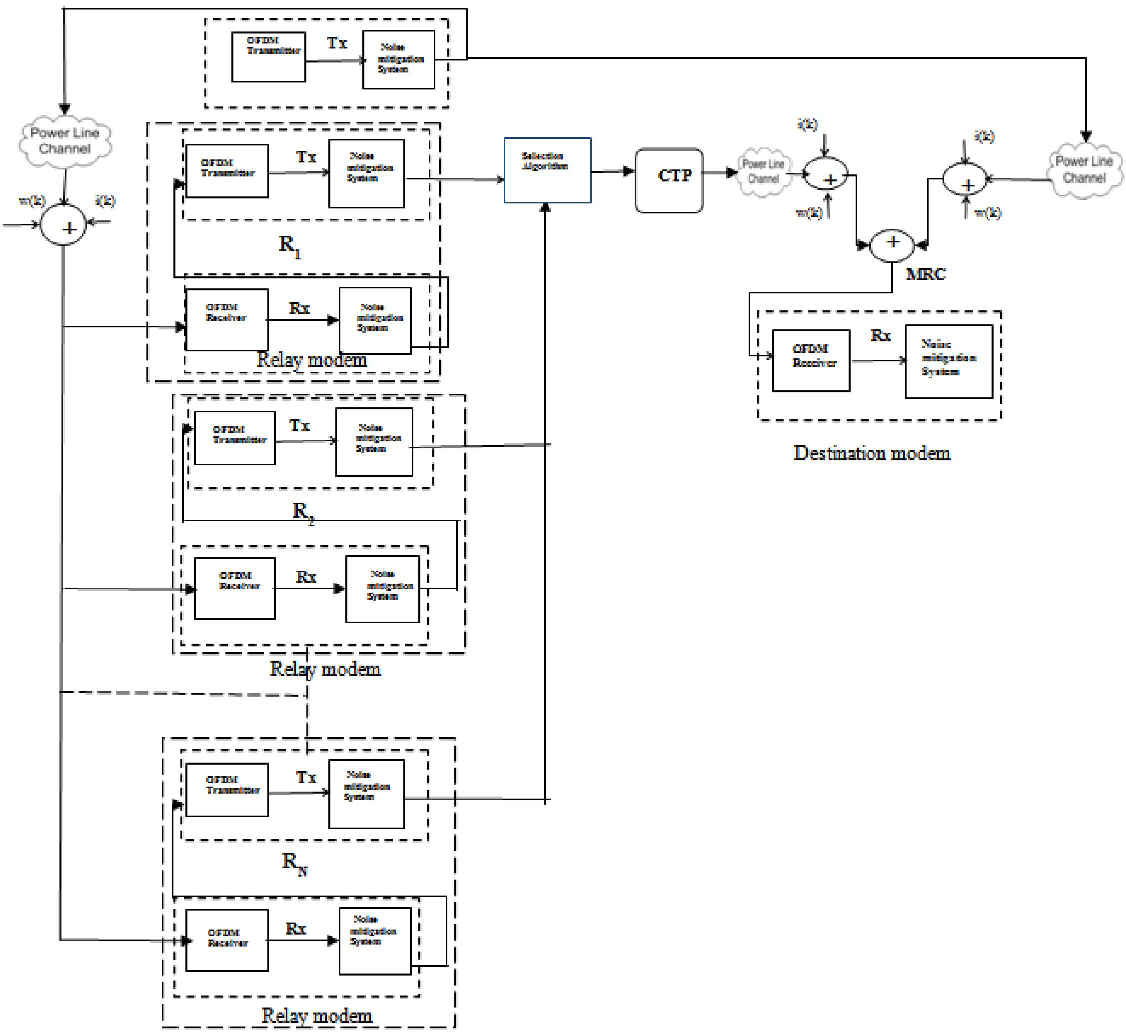
Several techniques of mitigating the identified effects in the PLC have been deployed ranging from use of repeaters to MIMO (within the wires of the cable) [1], [2], [3], [4], [5], but all of these techniques have one demerit or the other. Cost of deployment is a demerit in the use of repeaters while the presence of cross-talk among the wires is visible in MIMO. Cooperative relaying was deployed for achieving PLC reliability in [6], but the cooperative technique deployed is fixed relaying. Selective relaying was also investigated for the reliability of the cooperative broadband over powerline (SPLCC) using equal power allocation algorithm between the direct and the cooperative links[7]. Some form of performance was achieved.

So as to avoid interference of PLC signals with other signal in the PLC bandwidth, 0 – 30 MHz, the FEC instituted an electromagnetic compatibility (EMC) policy, which restricted the maximum transmittable power in PLC. Thus, increasing transmittable power beyond limit for better performance is not allowed. It is then necessary to optimise the limited transmittable power over the PL channel.

In this paper, optimal power allocation algorithm was developed and investigated on the selective cooperative relaying broadband over powerline (SPLCC) system for symbol error rate reduction and channel capacity enhancement. Two cooperative protocols, amplify-and-forward and decode-and-forward were deployed. A best relaying path selective algorithm was implemented on both protocols. The performance of the equal power allocation (EPA) selective cooperative PLC system was compared with the performance of the optimal power allocation (OPA) cooperative PLC scheme. Improvement in channel capacity and symbol error rate were achieved in the proposed scheme.

II. Materials and Methods

The system model in Fig. 1 consists of three segments, the source, the relay (multiple) and the destination segments. The source modem is a PLC base-station, which serves as the source of the information to be transmitted, this segment is depicted as an OFDM transmitter with noise mitigation system. The relay (multiple) is both an OFDM receiver and transmitter with noise mitigation, while the destination modem is represented as an OFDM receiver. The relay selection algorithm follows a set of instruction to select the best relay. All of these modems are PLC modem. The cooperative transmission protocol (CTP) is the process of cooperation that the relay passes her signal through before routing it to the destination, the types considered are amplify-and-forward and decode-and-forward.



Two transmission schemes are identifiable in cooperative relaying, broadcasting and cooperative.
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 equation (1) & (2), while (3) describes the noise components.

$$y_{sr}^{pl} = \sqrt{\frac{P_1}{N}} h_{sr}^{pl} x + n_{sr}^{pl} \quad (1)$$

$$y_{sd}^{pl} = \sqrt{\frac{P_1}{N}} h_{sd}^{pl} x + n_{sd}^{pl} \quad (2)$$

$$n_{sr}^{pl} = w_{sr} + i_{sr} \text{ and } n_{sd}^{pl} = w_{sd} + i_{sd} \text{ [8]} \quad (3)$$

Where P_1 is the PLC source transmit power and n_{sr}^{pl} and n_{sd}^{pl} are the noise at the source-destination and source-relay PL channels respectively. n_{sd}^{pl} n_{sr}^{pl} are constituted of coloured background noise and impulsive noise. *w* represents the coloured background noise and *i*, impulsive noise, which has a Gaussian amplitude and Poisson arrival

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

$$y_{rd}^{pl} = \sqrt{\frac{P_2}{N}} h_{rd}^{pl} q(y_{sr}^{pl}) + n_{rd}^{pl} \quad (4)$$

$$n_{rd}^{pl} = w_{rd} + i_{rd} \quad (5)$$

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

Let $\sqrt{\frac{P_1}{N}} = \sqrt{P_1^{\iota}}$ and $\sqrt{\frac{P_2}{N}} = \sqrt{P_2^{\iota}}$

For the PLC amplify-and-forward cooperation, relay received signal is made stronger by a factor β^{pl} [9]

$$\beta^{pl} = \frac{\sqrt{P_2^{\iota}}}{\sqrt{P_1^{\iota}\left|h_{sr}^{pl}\right|^2 + N_x}} \quad (6)$$

$$N_x = N_w + N_i \quad (7)$$

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

Where N_X is the noise PSD in the power line channel a sum of the PSD's in the AWGN and the impulsive noises.

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;

$$y_{rd}^{pl} = \beta^{pl} h_{rd}^{pl} y_{sr}^{pl} + n_{rd}^{pl} \text{ and } n_{rd}^{pl} = w_{rd} + i_{rd} \quad (8)$$

In the decode-and-forward scheme, 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

$$y_{rd}^{pl} = \sqrt{\beta_2^{pl}} h_{rd}^{pl} x + n_{rd}^{pl} \quad (9)$$

Where $\beta_2^{pl} = P_2^{\iota}$ if relay correctly decodes the transmitted signal and $\beta_2^{pl} = 0$ if otherwise. h_{rd}^{pl} and n_{rd}^{pl} are modelled as in PLC amplify and forward. The output at the destination for amplify-and-forward and decode-and-forward for correct decoding, is as represented in (10) and (11).

$$Y_{out}^{DF} = \sqrt{P_1^{\iota}}\, h_{sr}^{pl} x + n_{sr}^{pl} + \sqrt{P_2^{\iota}}\, h_{rd}^{pl} x + n_{rd}^{pl} \qquad (10)$$

$$y_d\left[n\right] = h_{s,d}^{*}\left[n\right] y_{s,d}\left[n\right] + h_{r,d}^{*}\left[n\right] y_{r,d}\left[n\right] \qquad (11)$$

Combining the signals at the destination using the *Maximum Ratio Combining (MRC)* yields;

$$Y_{out}^{MRCAF} = \left(\sqrt{P_1^{\iota}} \left|h_{sd}^{pl}\right|^2 + \frac{\sqrt{P_1^{\iota} P_2^{\iota}}}{\sqrt{P_1^{\iota} \left|h_{sr}^{pl}\right|^2 + N_x}} \left|h_{rd}^{pl}\right|^2 \left|h_{sr}^{pl}\right|^2 \right) x + \left(h_{sd}^{pl} n_{sd}^{pl} + \frac{\sqrt{P_2^{\iota}}}{\sqrt{P_1^{\iota} \left|h_{sr}^{pl}\right|^2 + N_x}} h_{rd}^{pl} n_{sr}^{pl} + h_{rd}^{pl} n_{rd}^{pl} \right) \qquad (13)$$

$$Y_{out}^{MRCDF} = \left(\sqrt{P_1^{\iota}} \left|h_{sd}^{pl}\right|^2 + \sqrt{P_2^{\iota}} \left|h_{rd}^{pl}\right|^2 \right) x + \left(\left|h_{sd}^{pl}\right|^2 n_{sd}^{pl} + \left|h_{rd}^{pl}\right|^2 n_{rd}^{pl} \right) \qquad (14)$$

Optimal Power Ratio

Equal power allocation (EPA) was deployed for the allocation of power to both transmission schemes (direct and cooperative) in the previous sections. Hence, $P_1 = \frac{1}{2} P_t$ and $P_2 = \frac{1}{2} P_t$, where P_1 is the power used for direct transmission and P_2 is the power used for the cooperative transmission from relay modem to destination modem. This may not yield the optimal system performance.

This section investigates a power allocation algorithm that will enhance optimal system performance. It implements a heuristic process to determine a transmittable power ratio that will be optimal for the power allocation [10]. The flow diagram in Figure shows the activities line-up for the section.

Heuristic Process

The particle swarm optimization (PSO) technique was deployed for the heuristic process. Transmittable power (P_t) represents the particle in the PSO and the target is channel capacity (*CC*). The PSO was used to either minimize or maximize P_1 and P_2 for optimality of the channel capacity.

The objective function for both P_{min} and P_{max} used to perform the optimization are as given in Eqns. 15 and 16.

$$P_{\min} = \sum_{i=1}^{n} P_t(i) - \frac{1}{n} P_t(i) \qquad (15)$$

$$P_{\max} = \sum_{i=1}^{n} P_t(i) + \frac{2}{n} P_t(i) \qquad (16)$$

Optimal Power Ratio Simulation

The PSO was simulated using the objective function described in Eqns. 15 and 16 for minimizing/maximizing the source power and relay power accordingly.

Five different power were identified following the EMC policy for the simulation. They are:

-12 dB, -11.25 dB, -12.3 dB, -11.98 dB and -12.35 dB [11].

One thousand samples over one thousand iteration was used to perform the simulation.

Figure 3.13 shows that the simulations converges around the five power levels used for the simulation and Table 3.2 shows the simulation result, which is the allocated power to source and relay (a function of the individual levels of power), for optimal performance.

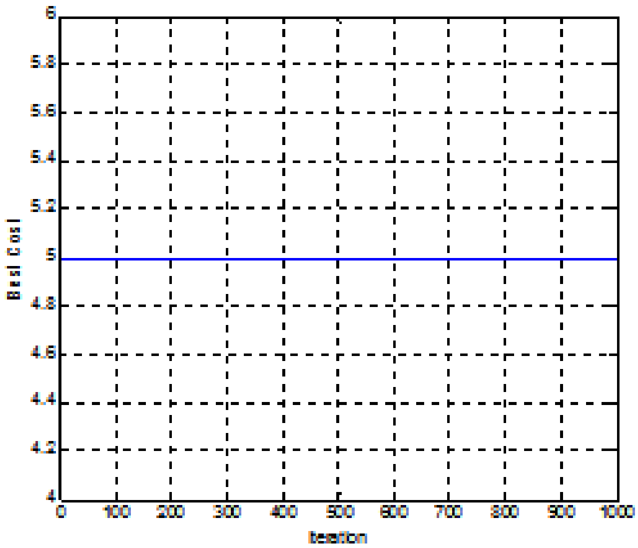


Table 3.2: Optimization Simulation Result

Optimization Result	Power Levels (dB)				
	-12	-11.25	-12.3	-11.98	-12.38
$P_{s(min)}$	-4.000	-3.750	-4.100	-3.993	-4.126
$P_{r(max)}$	-8.000	-7.500	-8.200	-7.987	-8.253

The result reveals that the source power is minimized while the relay power is maximized for optimal power performance. The optimized power expressed as a ratio of the available transmittable power is;

$$P_s = \frac{P_{s(min)}}{P} = \frac{-4.000}{-12} = \frac{1}{3} \quad (17)$$

and

$$P_r = \frac{P_{r(max)}}{P} = \frac{-8.000}{-12} = \frac{2}{3} \quad (18)$$

Therefore, for optimal system's performance, the source power was minimized from $\frac{1}{2}P_t$ to $\frac{1}{3}P_t$ and the relay power maximize from $\frac{1}{2}P_t$ to $\frac{2}{3}P_t$, hence power ratio allocation for optimal performance is P_s: $P_r = \frac{1}{3} : \frac{2}{3}$.

Optimal Power Allocation Algorithm

- The SNR of the relay channels to the source node are determined, for 3, 5 relay deployments.

$$\lambda_i^{pl} \; for \; i = 1,2,3.$$

$$\lambda_j^{pl} \; for \; j = 1,2,3,4,5.$$

These SNR values is made available to the source node.

- The source node selects the relay with the best SNR.
- The selected relay uses the two third of the transmit power to transmits its processed signal to the destination node (cooperative link). This implements optimal power allocation (OPA).

OPA SPLCC Channel Capacity Analysis

The optimal power algorithm was implemented using the optimal power ratio obtained in section in determining all the direct and relay channels SNR before obtaining the resultant SNRs' in all the subcarriers for both cooperative protocols for all relaying schemes. These SNRs' are as expressed in Eqns. 19 and 20. These were inserted into the expression for the channel capacity in Eqn. 21.

$$\lambda^{*pl}_{SAF} = \lambda^{*pl}_{sd} + \max_i \left(\lambda^{*pl}_{sid} \right) = \frac{A_3^2}{B_3} \quad (19)$$

$$A_3 = \left(\sqrt{P_1^*} \left| h_{sd}^{pl} \right|^2 + \max_i \left(\frac{\sqrt{P_1^* P_2^*}}{\sqrt{P_1^* \left| h_{si}^{pl} \right|^2 + N_x}} \left| h_{id}^{pl} \right|^2 \left| h_{si}^{pl} \right|^2 \right) \right) \text{ and } B_3 = \left(\left| h_{sd}^{pl} \right|^2 + \max_i \left(\left| h_{id}^{pl} \right|^2 \left(\frac{\sqrt{P_2^*}}{\sqrt{P_1^* \left| h_{si}^{pl} \right|^2 + N_x}} + 1 \right) \right) \right)$$

$$\lambda_{SDF}^{*pl} = \lambda_{sd}^{*pl} + \max_i \lambda_{id}^{*pl} = \frac{\left(\sqrt{P_1^*} \left| h_{sd}^{pl} \right|^2 \right)^2}{\left| h_{sd}^{pl} \right|^2} + \max_i \left(\frac{\left(\sqrt{P_2^*} \left| h_{id}^{pl} \right|^2 \right)^2}{\left| h_{id}^{pl} \right|^2} \right) \quad (20)$$

where $P_1^* = \dfrac{P_1}{N}, P_2^* = \dfrac{P_2}{N}$

$$C = \frac{B}{N} \sum_{k=0}^{N-1} \log_2 (1 + \lambda_u^{*pl}) \quad (21)$$

where $u \in \left(SAF_i^*, \text{SDF}_i^* \right)_{i=3,5.}$.

OPA SPLCC Symbol Error Rate Analysis

The formulation of the SER for the SAF and SDF SPLCC for optimal power allocation algorithm at destination node with QAM modulation are given in Eqns. 22 and 23;

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

(22)

where $\beta_1^{\iota *} = \max_i \left(N_x \big/ P_2^{'} \left| h_{si}^{pl} \right|^2 \right), \beta_2^{\iota *} = \max_i \left(N_x \big/ P_2^{'} \left| h_{id}^{pl} \right|^2 \right)$.

$$\chi_{SDF}^* = F_2 \left(1 + \frac{b_{QAM} P_1^{'} \left| h_{sd}^{pl} \right|^2}{2 N_x \sin^2 \theta} \right) F_2 \left(1 + \max_i \left(\frac{b_{QAM} P_1^{'} \left| h_{si}^{pl} \right|^2}{2 N_x \sin^2 \theta} \right) \right) + F_2 \left(\left(1 + \frac{b_{QAM} P_1^{'} \left| h_{sd}^{pl} \right|^2}{2 N_x \sin^2 \theta} \right) F_2 \left(1 + \max_i \left(\frac{b_{QAM} P_2^{'} \left| h_{id}^{pl} \right|^2}{2 N_x \sin^2 \theta} \right) \right) \right) \times \left[1 - F_2 \left(1 + \max_i \frac{b_{QAM} P_1^{'} \left| h_{si}^{pl} \right|^2}{2 N_x \sin^2 \theta} \right) \right]$$

(23)

SPLCC-OPA Simulation

The developed eqns. Were simulated for both cooperative protocols, amplify-and-forward and decode-and-forward. Other parameters used for the simulation are as specified in Table 1.

Table 3.1: Simulation Parameters

Parameters	Value	Parameters	Value
N (Number of taps)	20	Bandwidth	0 – 30 MHz
α_0 (offset attenuation)	0	Code rate (CC)	1/2
α_1(increase of attenuation)	1.6×10^{-10}	K (CC constraints)	8
k (exponent of attenuation)	1	IFFT Subcarriers	256
A (Impulsive noise index)	0.001	OFDM symbols	10
n (Reed-Solomon)	64	Cyclic prefix	64
k (Reed-Solomon)	48	Modulation scheme	16-QAM
N_o	-125	N1	35
f_1	3.6	P	-12.5dBmW
R	1	Length of Network	20 m

III. Results and Discussion

SPLCC OPA Channel Capacity Performance

The channel capacity performance for the proposed optimal power allocation algorithm, the equal power allocation, the fixed PLCC relaying and the benchmark schemes is depicted in Fig. 2. The performances are for 3 and 5 relays deployments for both AF and DF protocols, implementing equal power allocation (EPA) and optimal power allocation (OPA) algorithms

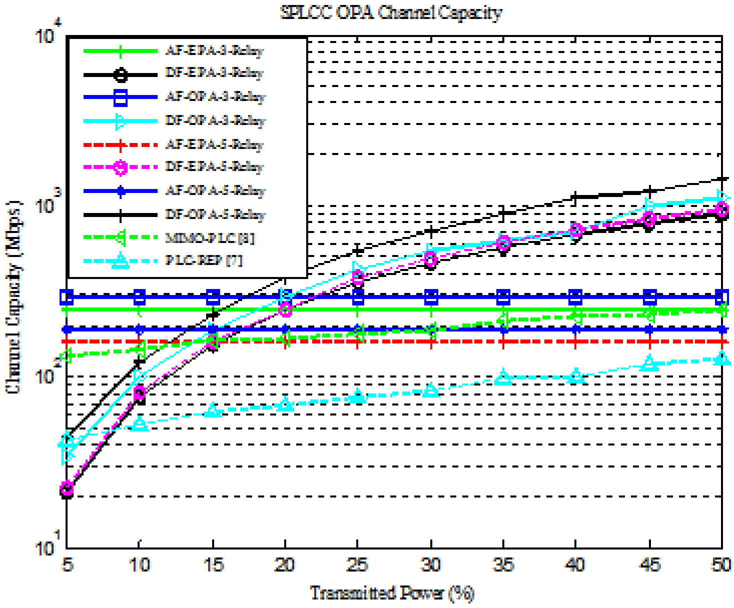


Figure 2: SPLCC OPA Channel Capacity Performance

The OPA algorithm improves the channel capacity on both the relay deployment scenarios on both cooperative links. Fig. 3 reveals that on the SAF link, the 3-R scenario yielded the best performance in channel capacity. For all percentage of transmitted power, this scenario reached a constant 290.3 Mbps as compared to the 248.3 Mbps of the EPA. An improvement of 19% in channel capacity was achieved over the EPA in the 5R deployment scenario.

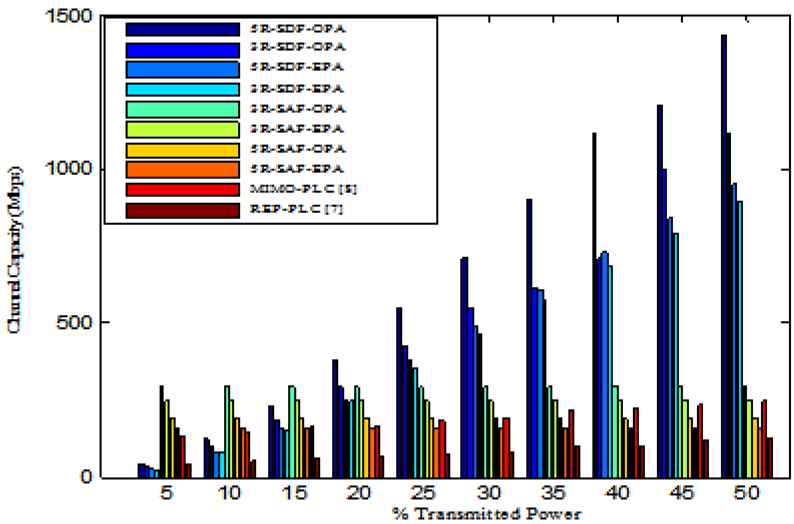


Table 2 shows the percentage improvement of the OPA over the EPA and MIMO-PLC on the SAF link when 15% of the source power was used for transmission (15% chosen for discussion from Fig. 3).

Table 2: Percentage Improvement of OPA on SAF Link at 15% Power Transmission

OPA	EPA (%)	MIMO-PLC (%)	PLC-REP
3R	19.97	73.8	Lot
5R	19	14.4	Lot

The SDF link in Fig.3 reveals that at percent power transmission power less than 20%, the OPA does not achieve any improvement in channel capacity over the MIMO-PLC, because less power was used in the transmission. But at other power percentages, appreciable improvement in CC was achieved. Table 3 shows the performance improvement in CC achieved by OPA scheme over the duo of EPA and MIMO-PLC schemes.

Table 3: OPA Channel Capacity Percent Improvement on SDF Link at 25% Power Transmission

OPA	EPA (%)	MIMO-PLC (%)	PLC-REP
3R	51.3	121	Lot
5R	83.5	184	Lot

On this link, the 5R-OPA scheme rendered the best improvement in CC over the EPA schemes.

SPLCC-OPA Symbol Error Rate Performance

The performance of the power ratio obtained in Chapter 3 for SER is compared with those of the equal power allocation obtained in previous section alongside those of fixed relaying, MIMO-PLC and PLC-repeater's in this section. The performances of those links is presented in Fig. 4.

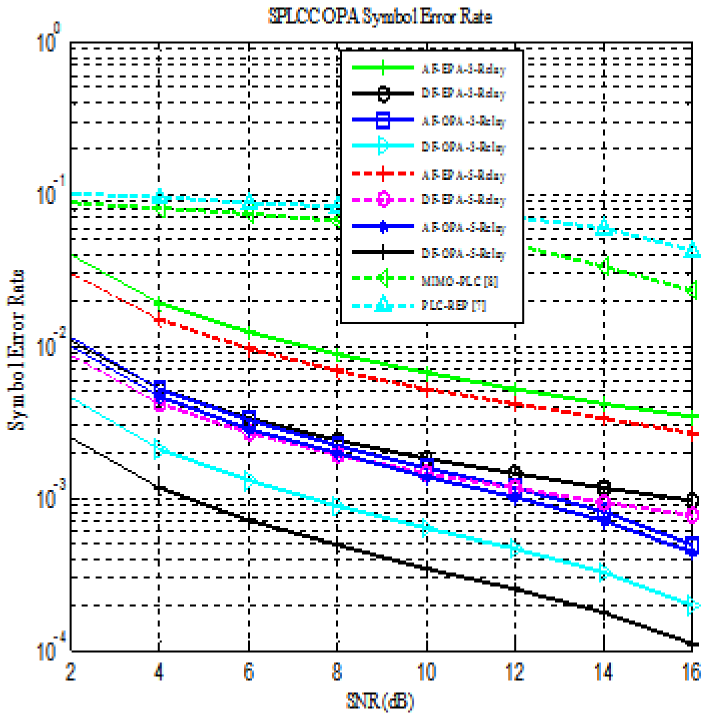


Figure 4: SPLCC OPA Symbol Error Rate Performance

The SAF links SER performance in Fig. 5reveals that the OPA presents a reduction in the number of symbols in error for all relay deployment scenarios. At 4 dB SNR, the OPA-3R performs the best while the OPA-5R yielded better performance as the SNR increases. At this SNR, the number of symbols in error for 1000 symbols transmitted is shown in Table 4.

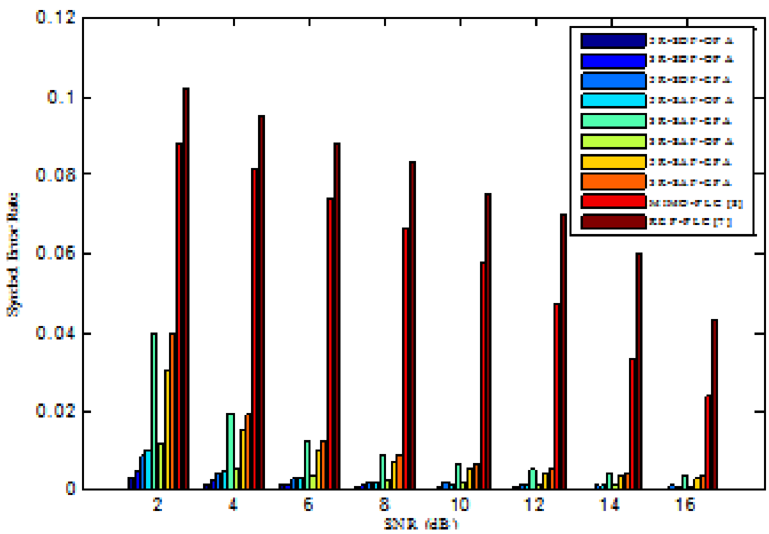


Table 4: SAF Symbols in Error at 4 dB SNR

Deployments	OPA	EPA	MIMO-PLC	PLC-REP
3R	5	19	84	Lot
5R	5	15	84	Lot

The SDF renders a further reduction in SER as depicted in Fig. 5, the OPA performing the best. Table 5 shows the symbol(s) in error with 1000 symbols transmission.

Table 5: SDF Symbols in Error at 4 dB SNR

Deployments	OPA	EPA	MIMO-PLC	PLC-REP
3R	2	5	84	Lot
5R	1	4	84	Lot

Examining Tables 4 and 5 shows that the OPA scheme for both cooperative protocols yielded an appreciable performance in symbol error reduction. For instance, only one (1) symbol will be in error, with SDF, on both relay scenarios at 5 dB SNR, while four (4) symbols will be in error with the EPA and for MIMO-PLC when 1000 symbols are transmitted.

IV. Conclusion

The suitability of the broadband over powerline for the provision of broadband data for various application is taking a prime place in the telecommunication world. The effect of optimal power allocation between the direct and cooperative links have been considered in this work. The optimal power allocation algorithm developed was deployed in a selective relaying cooperative broadband over powerline system. Improvement was achieved in the symbol error reduction on the optimal power system than the equal power allocation scheme. Furthermore, channel capacity is improved with the optimal power deployment than the equal power allocation. The duo of channel capacity and symbol error rate achieved improvement.

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