For More Energy-Efficient Dual-Hop DF Relaying Power-Line Communication Systems

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***Abstract*—Energy efficiency in multihop cooperative power-line communication (PLC) systems has recently received considerable attention in the literature. In order to make such systems more energy efficient, this paper proposes a relaying technique equipped with energy-harvesting capabilities. More specifically, we consider a dual-hop decode-and-forward (DF) broadband PLC relaying system in which the relay exploits the high noise inherent in PLC channels to further enhance energy efficiency; this system will be referred to as DF with energy harvesting (DF-EH). This study deploys, particularly, the time-switching relaying protocol for energy harvesting. An accurate analytical expression for the energy efficiency and a closed-form expression for the average outage probability of the proposed system are derived and then verified with Monte Carlo simulations. For the sake of comparison and to highlight the achievable gains, we also analyze the energy-efficiency performances and the average outage probabilities of the conventional DF relaying system, i.e., without energy harvesting, as well as that of the direct-link approach. Furthermore, various frequency selection and power allocation strategies, namely, optimal frequency selection, random frequency selection, and equal power allocation, exploiting the multiple power cables, are studied. Then, the impact of several system parameters such as the energy-harvesting time factor, various idle power consumption profiles, relay location, power allocation as well as different noise scenarios are examined. The results reveal that the proposed DF-EH system is able to provide energy efficiency improvements of more than 30% compared to the conventional DF relaying scheme. It is also shown that the proposed system with optimal frequency selection performs better at low SNR, whereas at high SNR the equal power allocation based system will have the best performance.**

***Index Terms*—Decode-and-forward (DF) relaying, energy efficiency, energy harvesting, impulsive noise, outage probability, power allocation, power-line communication (PLC).**

I. Introduction

POWER-LINE communication (PLC) technology, both narrowband and broadband, has enabled many smart grid applications and high-speed home-networking solutions [1]–[3]. On the one hand, the main advantage of this network over the other existing alternatives is that no new wiring installations are required. On the other hand, however, this vast infrastructure was never designed to carry communication signals at high frequencies, higher than 50 Hz in Europe or 60 Hz in the U.S., which consequently makes it a hostile communication medium. Such impairments include high levels of non-Gaussian interference, impedance mismatching, multipath fading, and high frequency-dependent attenuation increasing exponentially with distance [4]–[6]. Not only that, there is also the low transmit power restrictions that should comply with the regulations determined by independent and governmental regulatory agencies [7], [8], which leads to low signal-to-noise ratio (SNR) values at the receiving PLC modems and may severely deteriorate the communication performance of such systems.

In attempts to reduce the severity of these issues, researchers have proposed many techniques in the literature such as cooperative relaying systems including amplify-and-forward (AF) and decode-and-forward (DF) [9]–[11]. More specifically, Cheng *et al.* [11] have evaluated the performance of a dual-hop AF PLC system and have shown that considerable capacity improvements can be obtained compared to the direct-link (DL) scenario. In addition, [10] studied the opportunistic DF (ODF) scheme in in-home PLC networks where relaying is only exploited if it provides better performance than that of the DL approach, and similar conclusions were drawn.

Very recently, however, power consumption in multihop PLC systems has attracted a large amount of research attention as will be discussed in Section II. In this respect, this paper proposes to enhance the energy efficiency of DF relaying broadband PLC systems by scavenging the high unwanted energy of the impulsive noise present over PLC channels, which otherwise would be wasted or even constitute a major impediment to effective data communication. Such available energy can be intelligently harvested by the relaying PLC modems and then used to forward information, which can consequently make the relaying nodes less dependent on external power supplies; more details are provided in Section III-C. For more quantitative characterization of the system performance, we also analyze the energy efficiency of the conventional DF relaying PLC system, i.e., with no energy harvesting, as well as the DL approach.

The main contributions of this paper are as follows. First, we derive accurate analytical expressions for the energy efficiency and average outage probability of the DF with energy harvesting (DF-EH), conventional DF and DL systems, which are then validated with Monte Carlo simulations. Second, to

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further improve the energy efficiency, different frequency selection and power allocation schemes are deployed, namely, optimal frequency selection, random frequency selection, and equal power allocation. The other contribution resides in investigating the impact of the energy-harvesting time, idle power of PLC modems, and the relay location on the energy efficiency performance. Throughout our analysis, we assume that the PLC channel has log-normal distribution as reported in [12] and to characterize both the background and impulsive noise components over the PLC channel, we adopt the well-known Bernoulli–Gaussian noise model [13]–[15]. The results show that considerable energy efficiency improvements, up to 30%, can be attained with the proposed DF-EH relaying system compared to the conventional DF-based approach. It will also be shown that unlike the latter system which offers the best energy efficiency performance when the relay is located half-way between the source and destination, the optimal energy efficiency of the proposed scheme is achieved when the relay is placed before the midpoint; otherwise, both systems will have identical performance. Furthermore, it will be presented that the DF-EH system with optimal frequency selection is more energy efficient at low SNR values, whereas at high SNR, DF-EH with equal power allocation has the best performance.

The rest of this paper is organized as follows. Section II reviews and discusses the related work. Section III describes the system model including the adopted channel and noise models, the relaying and energy-harvesting protocols. Sections IV and V analyze the energy efficiency and average outage probability of the proposed DF-EH, conventional DF and DL systems. Some frequency selection and power allocation schemes are proposed in Section VI. In Section VII, we present and discuss some numerical examples and simulation results of the analytical expressions derived in this paper. Finally, Section VIII concludes the paper and outlines the main results.

II. Related Work

Many studies have recently appeared in the literature proposing to reduce transmit power consumption and improve energy efficiency of multihop PLC systems. For instance, in 2011, D'Alessandro *et al.* [16] proposed ODF relaying for PLC systems. Specifically, they considered dual-hop relaying in which the relay only cooperates when it provides capacity improvement over the DL approach. The authors showed that with respect to the DL scheme, the proposed system can save several dBs of transmit power. In 2012, D'Alessandro *et al.* extended their work in [17] to include opportunistic AF (OAF) relaying and interesting comparisons between different relaying and network scenarios were considered. In particular, it was presented that an ODF-PLC approach can generally outperform the OAF-PLC system. Note that the two studies above considered only minimizing the transmit power of PLC modems, also referred to as *dynamic* power. However, in 2014, Bakkali *et al.* [18] conducted extensive experimental measurements and indicated that PLC modems incur additional power consumption during transmission, referred to as *static* power; this is the power consumed by PLC modems when no data is being transmitted. With this in mind, in 2015, unlike [16] and [17], Bakkali *et al.* [19] investigated the energy-efficiency performance of a half-duplex DF PLC system taking into account both static and dynamic power consumption. Very recently, this work was extended in [20] to include energy-efficiency performance evaluation of DF multiple-input multiple-output (MIMO) PLC networks. The reader may refer to [21] for a comprehensive survey study on MIMO for PLCs, as well as to [22]–[24] and the references therein. Bakkali *et al.* [20] examined both uniform time allocation and optimal time allocation strategies and found that gains of up to 12.5 dB in transmit power can be attained relative to DL transmission. In addition, Gacanin *et al.* [25] proposed multidomain bidirectional communications with network coding to enhance energy efficiency in G.hn-based applications.

To the best of our knowledge, all the aforementioned studies have focused on only optimizing system parameters to reduce transmit power of PLC modems. In contrast, very recently, we proposed in [26], for the first time, energy harvesting of impulsive noise present over PLC channels to improve the energy efficiency of PLC systems. In this paper, dual-hop AF relaying and ideal-relaying energy-harvesting protocols were adopted, and an accurate analytical expression for the energy efficiency was derived.

Unlike [26], in this paper, we use DF relaying and time-switching energy-harvesting protocols[1]; hence, the analyses, results, and conclusions in our previous and current studies are fundamentally different and clearly distinguishable. The rationale for selecting DF relaying, and not AF as in [26], is because the former can offer better performance improvement compared to the latter. In addition, AF relaying over impulsive noise PLC channels does not always enhance performance as was recently found by Facina *et al.* [30]. As for the energy-harvesting protocol, the time-switching relaying scheme seems to be practically more appropriate for PLC channels than the ideal-relaying one adopted in [26], as it will be discussed later. The other fundamental difference that distinguishes the current work from [26] is the power consumption profile of the PLC modems used, which consists of dynamic power, static power, and idle power. Furthermore, in [26] only the energy efficiency performance was analyzed, whereas this paper analyzes also the average outage probability performance, and investigates the performance of various frequency selection and power allocation strategies.

III. System Model

A block diagram of the system under consideration is illustrated in Fig. 1(a), which consists of source, relaying, and destination PLC modems. The conventional DF relaying system and the DL approach are also demonstrated in Fig. 1(b) and (c), respectively. As shown, the proposed system uses a DF relay equipped with an energy harvester to harvest the high noise energy over the PLC channel and uses it to forward the source

[1] In the time-switching relaying protocol, the relay switches between information reception and noise energy harvesting, which will be discussed in more details in Section III-C. This protocol is well investigated in additive white Gaussian noise (AWGN) wireless systems, see, e.g., [27]–[29].

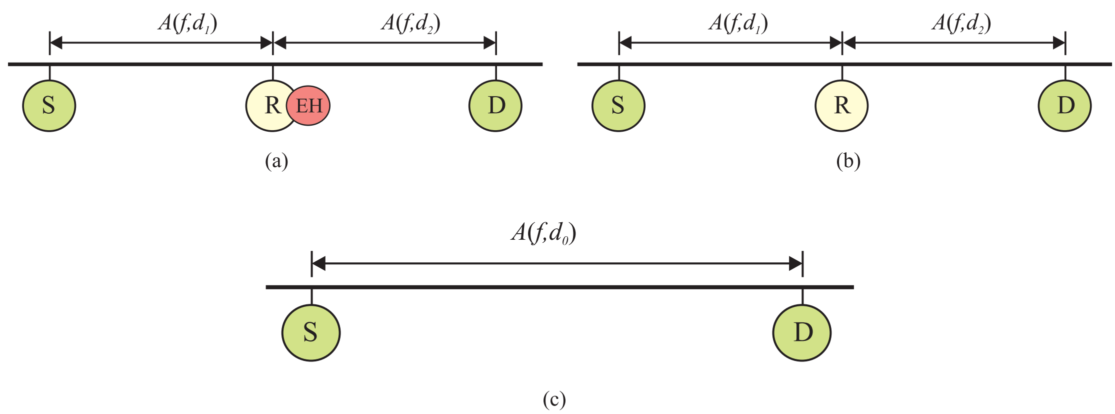

Fig. 1. Basic system diagrams of the three systems under consideration. Such a setup can be found in high-voltage and certain medium-voltage installations. The source, relay, and destination modems are represented by the letters S, R, and D, respectively. (a) DF-EH relaying PLC system. (b) Conventional DF relaying PLC system. (c) DL PLC system.

information. The two-term Bernoulli–Gaussian model is used to characterize both the background and impulsive noise and the PLC channel is assumed to be log-normally distributed. Furthermore, to more realistically evaluate the energy efficiency performance of PLC systems, our power consumption profile takes into consideration the static power, dynamic power, and idle power, all of which will be defined later.

A. Channel Model

The source–relay and relay–destination channel coefficients are represented as h_1 and h_2, and the corresponding distances are d_1 and d_2, respectively. For the DL system, the channel coefficient and the source-destination distance are denoted, respectively, as h_0 and $d_0 = d_1 + d_2$. For the relaying systems, the channels are assumed to be independent and identically distributed following the log-normal distribution with a probability density function (pdf)

$$f_{h_m}(z) = \frac{\zeta}{\sqrt{2\pi}\sigma_m z} \exp\left[-\frac{\left(10\log_{10}(z) - \mu_m\right)^2}{2\sigma_m^2}\right] \tag{1}$$

where $m \in \{0,\, 1,\, 2\}$, $\zeta = 10/\ln(10)$ is a scaling constant, μ_m and σ_m^2 (both in decibels) are the mean and the standard deviation of $10\,\log_{10}(h_m)$, respectively. In addition, because the PLC channel suffers from high distance- and frequency-dependent attenuation induced by the cable's imperfections, this impairment is also considered in our analysis and is denoted as $A(f,d)$, where f and d represent the operating frequency and distance, respectively.

B. Noise Model

To accurately characterize the PLC channel, the noise at all nodes is assumed to consist of both background and impulsive noise components. These noise types are modeled using the two-term Bernoulli–Gaussian noise model, [14], in which the background component n_w is considered complex Gaussian with zero mean and variance σ_w^2, whereas the impulsive part n_i is modeled as a Bernoulli–Gaussian random process. Hence

$$n = n_w + n_i \tag{2}$$

while n is the total noise $n_i = \mathtt{b}\,g$, g is complex white Gaussian noise with mean zero and $\mathtt{b}$ is the Bernoulli process with probability mass function

$$\Pr(\mathtt{b}) = \begin{cases} p, & \mathtt{b} = 1 \\ 1-p, & \mathtt{b} = 0 \end{cases} \tag{3}$$

and p is the probability occurrence of impulsive noise. Therefore, the pdf of the total noise can be simply expressed as

$$f_n(n) = p_0\,\mathcal{G}\left(n, 0, \sigma_w^2\right) + p_1\,\mathcal{G}\left(n, 0,\, \sigma_w^2 + \sigma_i^2\right) \tag{4}$$

where $p_0 = 1 - p$, $p_1 = p$, σ_i^2 is the impulsive noise variance and $\mathcal{G}$ represents the Gaussian pdf. From (4), it is clear that the total average noise power ρ_n^2 can be calculated as $\rho_n^2 = \sigma_w^2 + p\sigma_i^2$. The variances σ_w^2 and σ_i^2 basically define the input signal-to-background noise ratio (SBNR) and the signal-to-impulsive noise ratio (SINR), respectively, as follows: $\mathrm{SBNR} = 10\log_{10}\left(1/\sigma_w^2\right)$ and $\mathrm{SINR} = 10\log_{10}\left(1/\sigma_i^2\right)$. Without loss of generality, the noise characteristics in all our investigations are assumed to be identical at all PLC modems.

C. Relaying and Energy-Harvesting Protocols

For the DF relaying systems, with and without energy harvesting, it is assumed that there is no DL between the source and destination PLC modems due to the significant cable attenuation, which is a common assumption usually made when analyzing relaying systems; hence all communications are accomplished over two phases via the relay. The results based on this assumption will therefore establish the lower bound of the proposed system performance.

As for the energy-harvesting part, the energy harvester will be physically attached to the output of the impulsive noise detector, i.e., the system is not based on electromagnetic energy harvesting. The main motivation for this proposal is because all PLC modems available today already have the hardware and software capabilities to implement advanced algorithms to

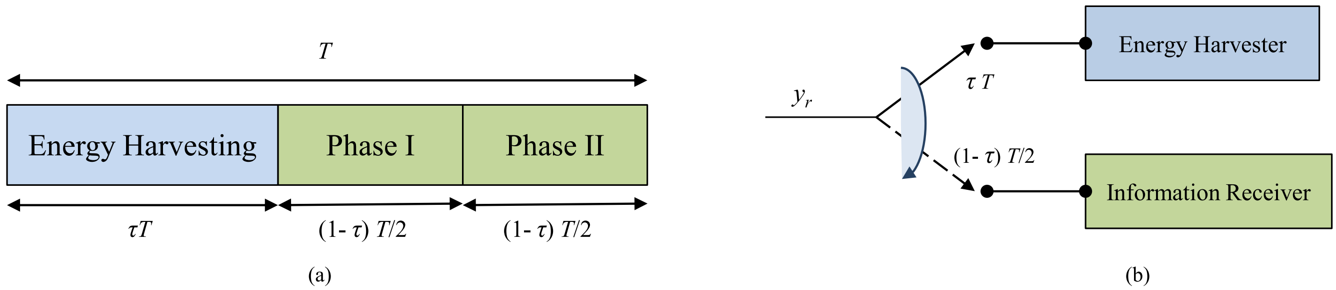

Fig. 2. Time-switching relaying protocol for energy harvesting and information signal processing at the relaying PLC modem. (a) Time frame structure in the time-switching relaying protocol. (b) Block diagram of the time-switching relaying system.

detect the PLC impulsive noise, which is then mostly nulled when it exceeds a predetermined threshold value. Although nulling is an efficient and simple way to improve the communication performance, the wasted energy due to this process does not maximize the energy efficiency of PLC systems. Instead of this energy-inefficient process, we propose to scavenge this energy using the time-switching relaying energy-harvesting protocol, the time frame structure, and block diagram of which are illustrated in Fig. 2.

As can be seen from Fig. 2(a), the time required to transmit one block from the source to the destination is given by T and the energy-harvesting time during which the relaying PLC modem harvests energy is denoted as τT, where $0 \leq \tau \leq 1$ is the energy-harvesting time factor. The remaining time is divided into two slots each of length $(1-\tau)\,T/2$ which are used for data transmission during phase I (source to relay) and phase II (relay to destination). This is to say that in the first $(1-\tau)\,T/2$ period, the source transmits its information to the relay and in the second $(1-\tau)\,T/2$ time slot the relay decodes, regenerates, and forwards this information to the destination modem. It is to be emphasized that the relaying modem is not entirely dependent on the harvested power P_{rh} but also has an external power source that provides P_{re} watts. It is also worthwhile pointing out that this paper neglects the power consumed by the circuitry to process data at the relaying PLC modem and hence all the available relay power $(P_{\mathrm{rh}} + P_{\mathrm{re}})$ will be used to forward the source signal.

D. Power Consumption Profile

For more realistic power consumption characterization, we consider in our work three power consumption modes defined as follows.

1) Dynamic power (P_{dyn}) is related to data transmission rate and will also be referred to, without loss of generality, as transmit power.
2) Static power (P_{stc}) corresponds to the baseline power consumed when no traffic is flowing through the PLC modem, i.e., circuitry consumption.
3) Idle power (P_{idl}) is, as the name suggests, the power consumed when the PLC modem is in power-saving idle mode, i.e., neither receiving nor transmitting.

With this in mind, we can write the total energy consumption for the proposed DF-EH relaying system, during phase I $\left(E_{t,1}^{\mathrm{DF-EH}}\right)$ and phase II $\left(E_{t,2}^{\mathrm{DF-EH}}\right)$, respectively, as

$$E_{t,1}^{\mathrm{DF-EH}} = \frac{(1-\tau)\,T}{2}\underbrace{\left(P_{\mathrm{dyn}}^{S} + P_{\mathrm{stc}}^{S} + P_{\mathrm{stc}}^{R} + P_{\mathrm{idl}}^{D}\right)}_{P_{t,1}^{\mathrm{DF-EH}}} \tag{5a}$$

$$E_{t,2}^{\mathrm{DF-EH}} = \frac{(1-\tau)\,T}{2}\underbrace{\left(P_{\mathrm{idl}}^{S} + P_{\mathrm{dyn}}^{R} + P_{\mathrm{stc}}^{R} + P_{\mathrm{stc}}^{D}\right)}_{P_{t,2}^{\mathrm{DF-EH}}} \tag{5b}$$

where the superscripts S, R, and D denote the corresponding power consumption at the source, relay, and destination modems, respectively, whereas $P_{t,1}^{\mathrm{DF-EH}}$ and $P_{t,2}^{\mathrm{DF-EH}}$ are the total transmit powers during phase I and phase II, respectively. Assuming that all the PLC modems are identical and therefore have same power consumption features, i.e., $P_{\mathrm{dyn}} = P_{\mathrm{dyn}}^{S} = P_{\mathrm{dyn}}^{R} = P_{\mathrm{dyn}}^{D}$, $P_{\mathrm{stc}} = P_{\mathrm{stc}}^{S} = P_{\mathrm{stc}}^{R} = P_{\mathrm{stc}}^{D}$, and $P_{\mathrm{idl}} = P_{\mathrm{idl}}^{S} = P_{\mathrm{idl}}^{R} = P_{\mathrm{idl}}^{D}$, (5a) and (5b) can be simplified to

$$E_{t,1}^{\mathrm{DF-EH}} = E_{t,2}^{\mathrm{DF-EH}} = \frac{(1-\tau)\,T}{2}\left(P_{\mathrm{dyn}} + 2P_{\mathrm{stc}} + P_{\mathrm{idl}}\right). \tag{6}$$

Similarly, and with the same assumption that all modems have identical power consumption properties, the total energy consumption for the conventional DF relaying and DL systems can be, respectively, expressed as

$$E_{t}^{\mathrm{DF}} = T\left(P_{\mathrm{dyn}} + 2P_{\mathrm{stc}} + P_{\mathrm{idl}}\right) \tag{7}$$

and

$$E_{t}^{\mathrm{DL}} = T\left(P_{\mathrm{dyn}} + 2P_{\mathrm{stc}}\right). \tag{8}$$

Having a closer look at (7) and (8), it can be deduced that the DL approach will have energy consumption of P_{idle} lower than that of conventional DF relaying when the source-destination distance is small, i.e., the path loss is negligible. On the other hand, however, if the two modems are distant, i.e., path loss is significantly high, the energy efficiency gain obtained using DF relaying will outweigh the loss due to the extra energy consumption, P_{idle} watts; hence DF relaying will offer better energy efficiency.

IV. Energy Efficiency Performance Analysis

In this section, we derive analytical expressions for the energy efficiency of the proposed DF-EH system as well as the conventional DF system and the DL approach.

A. DF-EH Relaying PLC System

As discussed above, the overall source-destination communication is accomplished over two phases. In the first phase, the received signal at the relay can be expressed as

$$y_r = \sqrt{P_s}\, A\left(f, d_1\right) h_1\, s + n_r \tag{9}$$

where P_s is the source PLC modem transmit power, $A\left(f, d_1\right)$ is the source-relay link attenuation, s is the source information signal normalized as $\mathbb{E}\left[|s|^2\right] = 1$, and n_r is the noise signal at the relaying modem with variance σ_r^2.

Assuming that all nodes are perfectly synchronized, the harvested energy at the relay can be written as

$$E_H = \kappa\, \tau T\, \sigma_r^2 \tag{10}$$

where $0 < \kappa < 1$ is the energy-harvesting efficiency determined mainly by the circuitry of the energy harvester at the relay. After decoding, remodulating, and forwarding the source information signal, the received signal at the destination modem can now be expressed as

$$y_d = \underbrace{\sqrt{P_r}\, A\left(f, d_2\right) h_2\, \bar{s}}_{\text{Signal Part}} + n_d \tag{11}$$

where $A\left(f, d_2\right)$ is the relay-destination link attenuation, $\bar{s}$ is the decoded version of the source signal, $P_r = P_{\mathrm{re}} + P_{\mathrm{rh}}$ is the relay total transmit power, P_{re} is the relay transmit power from the external power source, and P_{rh} is the relay harvested power. The harvested power is basically the harvested energy, given by (10), divided by the energy-harvesting time, i.e.,

$$P_{\mathrm{rh}} = \frac{E_H}{\left(1-\tau\right) T/2} = \frac{\tau}{\left(1-\tau\right)} 2\kappa\sigma_r^2. \tag{12}$$

To find the received signal at the destination as a function of the harvested power, we substitute (12) into (11), which yields

$$y_d = \underbrace{\sqrt{\frac{\tau}{\left(1-\tau\right)} 2\kappa\sigma_r^2 + P_{\mathrm{re}}}\, A\left(f, d_2\right) h_2\, \bar{s}}_{\text{Signal Part}} + n_d \tag{13}$$

where n_d is the noise signal at the destination modem with variance σ_d^2.

Now, grouping the information and noise terms in (9) and (13), we can obtain the SNR at the relay modem $\left(\gamma_r\right)$ and the SNR at the destination modem $\left(\gamma_d\right)$, respectively, as follows

$$\gamma_r = \frac{P_s\, A\left(f, d_1\right) h_1^2}{\sigma_r^2} \tag{14}$$

and

$$\gamma_d = \frac{\left(2\kappa\tau\sigma_r^2 + \left(1-\tau\right) P_{\mathrm{re}}\right)\, A\left(f, d_2\right) h_2^2}{\left(1-\tau\right) \sigma_d^2}. \tag{15}$$

The energy efficiency (η), in bps/Hz/W, or equivalently in bits/Hz/Joule, of the dual-hop DF system is determined by the minimum energy efficiency of the source-relay and relay-destination links, that is,

$$\eta = \min\left\{\eta_r\left(\gamma_r\right), \eta_d\left(\gamma_r\right)\right\} \tag{16}$$

where η_r and η_d are the energy efficiencies of the source-relay and relay-destination links, respectively. Since the energy efficiency is generally given by the ratio between the spectral efficiency (ξ) and total transmit power, the source-relay and relay-destination energy efficiencies can be calculated, respectively, as

$$\eta_r = \frac{\xi_r}{P_{t,1}^{\mathrm{DF}}} \tag{17a}$$

$$\eta_d = \frac{\xi_d}{P_{t,2}^{\mathrm{DF}}} \tag{17b}$$

where $P_{t,1}^{\mathrm{DF-EH}}$ and $P_{t,2}^{\mathrm{DF-EH}}$ are defined in (5).

For non-Gaussian impulsive noise channels, the instantaneous spectral efficiency is determined as [31]

$$\xi_j = p_0 \log_2\left(1+\gamma_j\right) + p_1 \log_2\left(1 + \frac{\gamma_j}{\beta}\right) \tag{18}$$

where $j \in \{r, d\}$, γ is the SBNR at the receiving modem and $\beta = 1 + \sigma_i^2/\sigma_w^2$. To determine the end-to-end average spectral and energy efficiencies of the proposed DF-EH system, we first need to derive these efficiencies for the source-relay and relay-destination links as follows.

1) Source-Relay Link: To begin with, and using (18), the source-relay link's average spectral efficiency in the presence of impulsive noise can be written as

$$\xi_r = \frac{\left(1-\tau\right)}{2} \sum_{m=0}^{1} p_m\, \mathbb{E}\left[\log_2\left(1+\gamma_{r,m}\right)\right] \tag{19}$$

where $\mathbb{E}\left[\cdot\right]$ denotes the expectation operator, $\gamma_{r,0} = \gamma_r$ and $\gamma_{r,1} = \gamma_r/\beta$. Equation (19) can be mathematically calculated as

$$\xi_r = \frac{\left(1-\tau\right)}{2} \sum_{m=0}^{1} p_m \int_0^\infty \log_2\left(1+\gamma\right) f_{\gamma_{r,m}}\left(\gamma\right) d\gamma \tag{20}$$

where $f_{\gamma_{r,0}}\left(\cdot\right)$ and $f_{\gamma_{r,1}}\left(\cdot\right)$ are the pdfs of $\gamma_{r,0}$ and $\gamma_{r,1}$, respectively. Now, given that γ is log-normally distributed and using the standard pdf formula of the log-normal distribution, the aforementioned pdfs can be expressed as

$$f_{\gamma_{r,m}}\left(\gamma\right) = \frac{\zeta}{\gamma\sqrt{8\pi}\sigma_1} \exp\left[-\frac{\left(\zeta \ln\left(\gamma\right) - \left(2\mu_1 + \zeta \ln\left(a_m\right)\right)\right)^2}{8\sigma_1^2}\right] \tag{21}$$

where $m \in \{0, 1\}$, $a_0 = P_s\, A\left(f, d_1\right)/\sigma_r^2$, and $a_1 = a_0/\beta$. Although it is difficult to get closed-form solutions for the integrals in (20), this can be straightforwardly and accurately approximated using Hermite–Gauss quadrature as follows. To do this, we first let

$$x = \frac{\zeta \ln\left(\gamma\right) - 2\mu_1 - \zeta \ln\left(a_m\right)}{\sqrt{8\sigma_1^2}}. \tag{22}$$

Using (22), we can rewrite (20) as

$$\xi_r = \frac{\left(1-\tau\right)}{2} \sum_{m=0}^{1} \int_{-\infty}^{\infty} \frac{p_m}{\sqrt{\pi}}\, h\left(x\right) \exp\left[-x^2\right] dx \tag{23}$$

which can consequently be calculated using the Hermite–Gauss quadrature as [32]

$$\xi_r \simeq \frac{(1-\tau)}{2} \sum_{m=0}^{1} \sum_{n=1}^{N} \frac{p_m}{\sqrt{\pi}} w_n h(x_n) \tag{24}$$

where

$$h(x_n) = \log_2 \left(1 + \exp\left[\frac{\sqrt{8}\sigma_1 x_n + 2\mu_1 + \zeta \ln(a_m)}{\zeta}\right]\right) \tag{25}$$

and $\{w_n\}_{n=1}^N$ and $\{x_n\}_{n=1}^N$ are the weights and abscissas of the N-point Hermite–Gauss quadrature tabulated in [33, Table 25.10]. It should be mentioned that we will consider $N = 20$ in all our evaluations since this value was found to be sufficiently large to achieve good accuracy. Now, using (5a), (17a), (24), and (25), the energy efficiency of the source-relay link can be written as

$$\begin{aligned}\eta_r = &\frac{(1-\tau)}{2(P_{\text{dyn}} + 2P_{\text{stc}} + P_{\text{idl}})} \\ &\times \sum_{m=0}^{1} \sum_{n=1}^{N} \left\{ \frac{p_m w_n}{\sqrt{\pi}} \right. \\ &\left. \times \log_2 \left(1 + \exp\left[\frac{\sqrt{8}\sigma_1 x_n + 2\mu_1 + \zeta \ln(a_m)}{\zeta}\right]\right)\right\}.\end{aligned} \tag{26}$$

This expression calculates the quantity of information transmitted from the source to the relay per unit energy use. Clearly, this equation is a function of the source-relay channel parameters such as σ_1, μ_1, d_1 as well as the dynamic, static, and idle powers of the deployed PLC modems. It is also interesting to observe that increasing the static and/or the idle power will always have a negative impact on the energy efficiency performance.

2) Relay-Destination Link: On the other hand, the energy efficiency derivation of the relay-destination link η_d is omitted in this paper for the sake of brevity, since it can be straightforwardly obtained from (26) by making the following substitutions: $a_0 = \left(2\kappa\tau\sigma_r^2 + (1-\tau) P_{\text{re}}\right) A(f, d_2) \,/\, (1-\tau)\sigma_d^2$, $a_1 = a_0/\beta$, $\sigma_1^2 = \sigma_2^2$, and $\mu_1 = \mu_2$.

Finally, substituting η_r and η_d into (16) yields the over all energy efficiency of the proposed DF-EH system. Although, it is not easy to express this in closed form, it does not pose any difficulty to find the solution numerically using software tools such as Mathematica or MATLAB.

B. Conventional DF Relaying System

Unlike the DF-EH approach, which has an additional EH-based source, the conventional DF system, illustrated in Fig. 1(b), relies entirely on the external power supply and is considered here to provide a quantitative comparison with the proposed system and to highlight the achievable gains. The energy efficiency of the conventional DF system can be easily obtained by following the same procedure as above while using $P_{\text{rh}} = 0$ and $\tau = 0$; also because of space limitations, the corresponding analytical expression is omitted here.

C. DL System

Below we analyze the performance of the DL system, shown in Fig. 1(c). In this configuration, the received signal at the destination can be simply written as

$$y_d = \sqrt{P_s}\, A(f, d_1 + d_2)\, h_0\, s + n_d \tag{27}$$

where $A(f, d_1 + d_2)$ is basically the attenuation of the source-destination channel.

Grouping the information and noise components in (27), we can express the SNR at the destination modem as

$$\gamma_d = \frac{P_s\, (A(f, d_1) + A(f, d_2))\, h_0^2}{\sigma_d^2}. \tag{28}$$

Now, using (8) and (28), and following the same steps in Section IV-A1, the energy efficiency of the DL system can be given by

$$\begin{aligned}\eta^{\text{DL}} = &\frac{1}{P_{\text{dyn}} + 2P_{\text{stc}}} \\ &\times \sum_{m=0}^{1} \sum_{n=1}^{N} \left\{ \frac{p_m w_n}{\sqrt{\pi}} \right. \\ &\left. \times \log_2 \left(1 + \exp\left[\frac{\sqrt{8}\sigma_0 x_n + 2\mu_0 + \zeta \ln(c_m)}{\zeta}\right]\right)\right\}\end{aligned} \tag{29}$$

where $c_0 = P_s\, (A(f, d_1) + A(f, d_2))/\sigma_d^2$ and $c_1 = c_0/\beta$. This equation calculates the quantity of information transmitted from the source to the destination per unit energy use. It is clear from (29), in comparison to (26), that the factor $\frac{1}{2}$ is no longer present because the overall source-destination communication is now accomplished over only one hop. It is also evident that the idle power component no longer appears in (29), unlike (26).

V. Average Outage Probability

In this section, we analyze the average outage probability of the energy efficiency for the three systems under study. This probability is defined as the probability that the instantaneous energy efficiency falls below a certain threshold value (η_{th}) and is given mathematically as

$$\mathcal{O}(\eta_{\text{th}}) = \Pr\{\eta < \eta_{\text{th}}\}. \tag{30}$$

A. DF-EH Relaying PLC System

To find the end-to-end outage probability of this system, we first need to derive the outage probability of the source-relay and relay-destination links. Using (5a) and (17a), the outage probability of the first link can be given as

$$\mathcal{O}(\eta_{\text{th}}) = \Pr\left\{\frac{(1-\tau)\,\xi_r}{2(P_{\text{dyn}} + 2P_{\text{stc}} + P_{\text{idl}})} < \eta_{\text{th}}\right\} \tag{31}$$

where ξ_r is given by (18).

Using (18), we can rewrite (31) as

$$\mathcal{O}\left(\eta_{\rm th}\right) = \Pr\left\{\frac{(1-\tau)}{2}\frac{\sum\limits_{m=0}^{1} p_m \log_2\left(1+\gamma_{r,m}\right)}{\left(P_{\rm dyn}+2P_{\rm stc}+P_{\rm idl}\right)} < \eta_{\rm th}\right\}. \tag{32}$$

To simplify our analysis in this section, we use the high SNR approximation [34]. With this in mind, and with some basic algebraic manipulation, (32) can now be simplified to

$$\mathcal{O}^H\left(\eta_{\rm th}\right) \backsimeq \Pr\left\{\sum_{m=0}^{1}\log_2\left(\gamma_{r,m}\right)^{p_m} < \frac{2\eta_{\rm th}\left(P_{\rm dyn}+2P_{\rm stc}+P_{\rm idl}\right)}{(1-\tau)}\right\}. \tag{33}$$

Since $\gamma_{r,0} = \gamma_r$ and $\gamma_{r,1} = \gamma_r/\beta$, we can rewrite (33) as

$$\mathcal{O}^H\left(\eta_{\rm th}\right) \backsimeq \Pr\left\{\gamma_r < \beta^p 2^{\frac{2\eta_{\rm th}}{(1-\tau)}\left(P_{\rm dyn}+2P_{\rm stc}+P_{\rm idl}\right)}\right\} \tag{34}$$

which can also be expressed as follows:

$$\mathcal{O}^H\left(\eta_{\rm th}\right) \backsimeq F_{\gamma_r}\left(\beta^p 2^{\frac{2\eta_{\rm th}}{(1-\tau)}\left(P_{\rm dyn}+2P_{\rm stc}+P_{\rm idl}\right)}\right) \tag{35}$$

where $F_{\gamma_r}(\cdot)$ is the cumulative distribution function of γ_r, given by (36), shown at the bottom of the page.

Finally, using the log-normal distribution properties, the overall outage probability of the DF-EH system can be written as in (36), where $a_1 = P_s A(f,d_1)/\sigma_r^2$ and $a_2 = \left(2\kappa\tau\sigma_r^2 + (1-\tau)P_{\rm re}\right)A(f,d_2)/(1-\tau)\sigma_d^2$.

B. Conventional DF Relaying and DL Systems

Following similar procedure in the previous section, it is straightforward to show that the average outage probability of the conventional DF relaying system and the DL approach can be given by (37) and (38), respectively, shown at the bottom of this page, where $b_1 = P_s A(f,d_1)/\sigma_r^2$ and $b_2 = P_{\rm re} A(f,d_2)/\sigma_d^2$.

These expressions will be used later to obtain some numerical results which will provide very useful comparisons between the performances of the three systems under consideration. Now, in order to further improve the energy efficiency of PLC systems, we next exploit the existing multiple power cables with which different frequency selection and power allocation strategies can be implemented.

VI. Frequency Selection and Power Allocation

In this section, we exploit the existing multiple cables of the power line network and implement frequency selection and power allocation. In frequency selection, all the available power is allocated to one channel depending on the selection criteria. Here, we consider two frequency selection schemes as follows.

1) Optimal frequency selection where all the available power is allocated to the channel with the highest SNR. That is, for the source-relay link in the proposed DF-EH system, the corresponding problem can be formulated as

$$\max_{\{n\}} \frac{(1-\tau^*)}{2\,P_{t,1}^{\rm DF-EH}}\sum_{m=0}^{1} p_m \mathbb{E}\left[\log_2\left(1+b_m h_{n,m}^2 P_s\right)\right] \tag{39}$$

where $b_0 = A(f,d_1)/\sigma_r^2$, $b_1 = b_0/\beta$ and n denotes the cable index which is three in this study. Note that in order to achieve optimal performance, channel state information (CSI) should be perfectly known at the source and relaying PLC modems, which can be simply obtained by a feedback channel.

2) Random frequency selection, where the channel is generally selected randomly. This scheme, as will be shown later, has the worst performance compared to other systems; however, this scheme can still be desirable in systems that require higher security since it provides random hopping between different cables making it more challenging to eavesdrop information. In addition, it is simple to implement compared to the other approaches.

When no CSI is available at the transmitting PLC modem, equal power allocation, i.e., dividing the total available power equally over the cables, becomes an attractive solution. Therefore, the performance of this scheme will also be evaluated in Section VII. The energy efficiency with this configuration for the source-relay link of the proposed DF-EH system can be calculated as

$$\eta_r = \frac{(1-\tau^*)}{2\,P_t^{\rm DF-EH}}\sum_{n=1}^{3}\sum_{m=0}^{1} p_m \mathbb{E}\left[\log_2\left(1+b_m h_{n,m}^2\frac{P_s}{3}\right)\right]. \tag{40}$$

In this equation, the total transmit power is divided by three since the maximum number of available power cables is three. It is worth pointing out here that Axell *et al.* [35] have recently reported that the so-called water-filling solution, which is the optimal power allocation solution over AWGN channels, is not

$$\mathcal{O}_{\rm EH}^H\left(\eta_{\rm th}\right) = 1 - \prod_{i=1}^{2}\left(\frac{1}{2}\,{\rm Erfc}\left[\frac{\zeta\ln\left[\beta^p 2^{\frac{2\eta_{\rm th}}{(1-\tau)}\left(P_{\rm dyn}+2P_{\rm stc}+P_{\rm idl}\right)}\right] - \left(2\mu_i + \zeta\ln\left[a_i\right]\right)}{2\sqrt{2}\sigma_i}\right]\right) \tag{36}$$

$$\mathcal{O}_{\rm DF}^H\left(\eta_{\rm th}\right) = 1 - \prod_{i=1}^{2}\left(\frac{1}{2}\,{\rm Erfc}\left[\frac{\zeta\ln\left[\beta^p 2^{2\eta_{\rm th}\left(P_{\rm dyn}+2P_{\rm stc}+P_{\rm idl}\right)}\right] - \left(2\mu_i + \zeta\ln\left[b_i\right]\right)}{2\sqrt{2}\sigma_i}\right]\right) \tag{37}$$

$$\mathcal{O}_{\rm DL}^H\left(\eta_{\rm th}\right) = 1 - \frac{1}{2}\,{\rm Erfc}\left[\frac{\zeta\ln\left[\beta^p 2^{\eta_{\rm th}\left(P_{\rm dyn}+2P_{\rm stc}\right)}\right] - \left(2\mu_0 + \zeta\ln\left[\frac{(P_s+P_{\rm re})}{\sigma_d^2}\,{\rm Exp}\left[-2\alpha d_0\right]\right]\right)}{2\sqrt{2}\sigma_0}\right] \tag{38}$$

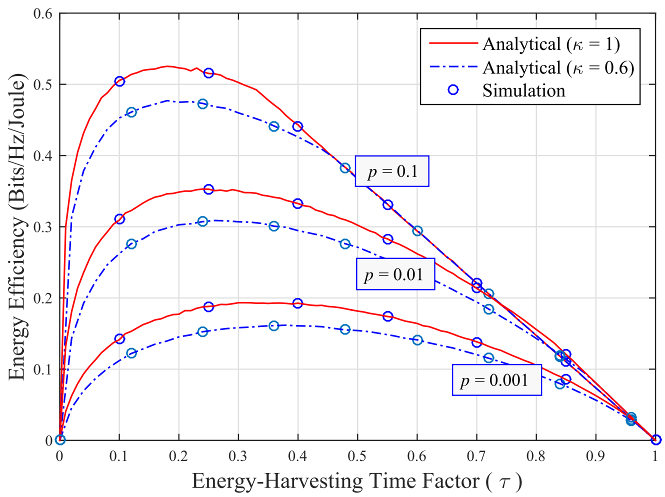

Fig. 3. Energy-efficiency performance versus the energy-harvesting time factor for different values of the impulsive noise probability and energy harvester efficiency.

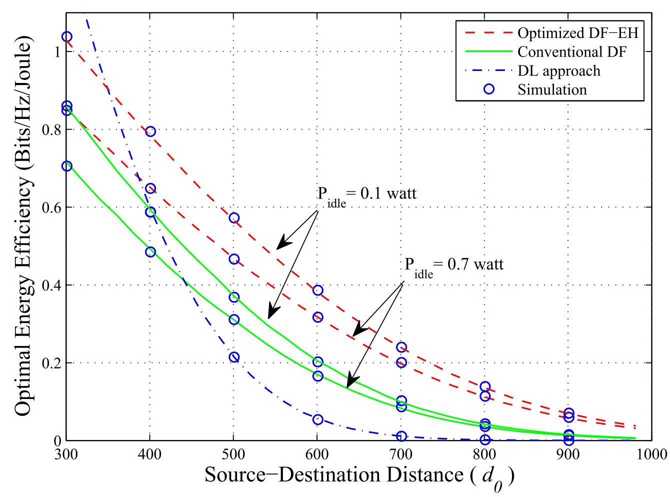

Fig. 4. Energy-efficiency performance with respect to the source-destination distance for the optimized DF-EH, conventional DF, and DL systems with different values of the idle power.

optimal over impulsive noise channels with different impulsive characteristics.

VII. Numerical Results

In this section, we present some numerical examples of the analytical expressions derived above to illustrate the impact of various system parameters on the energy efficiency and average outage probability of the three considered systems. To validate these expressions, we provide Monte Carlo simulations based on 10^6 iterations. The distance- and frequency-dependent attenuation model used here is given by $A(f,d) = \exp(-\alpha d)$, where $\alpha = a_o + a_1 f^k$ is the attenuation factor, d is the distance in meters, f is the operating frequency in MHz, k is the exponent of the attenuation factor, and a_o and a_1 are constants determined from measurements. Specifically, since an indoor broadband PLC channel is assumed, we use $a_0 = 9.4 \times 10^{-3}$, $a_1 = 4.2 \times 10^{-7}$, $f = 30$ MHz, and $k = 0.7$ [4], [36]. Although we consider in this section a wide range of system parameters, unless clearly stated otherwise, we will be using $P_s = P_{\rm re} = 1$ W, channels variances $\sigma_0^2 = \sigma_1^2 = \sigma_2^2 = 4$ dB, channels means $\mu_0 = \mu_1 = \mu_2 = 3$ dB, and SBNR at all nodes is 25 dB.

A. Energy-Harvesting Time Factor

To begin with, we investigate the impact of the energy-harvesting time factor on the energy efficiency performance of the proposed DF-EH system. To keep the focus on the influence of the energy harvested, we assume, only in this section, that $P_{\rm re} = 0$ W and therefore the relaying PLC modem relies entirely on the harvested energy. It is also assumed that the relay is positioned midway between the source and destination modems, such that $d_1 = d_2 = 50$ m, i.e., $d_0 = 100$ m, $P_{\rm stc} = 0.9$ W, $P_{\rm idle} = 0.1$ W, and SINR $= -10$ dB. Under these conditions, we plot in Fig. 3 the analytical and simulated energy efficiency performances versus the energy-harvesting time factor for different values of p and κ.

The first observation one can see from these results is that for a given energy-harvesting time, higher noise pulse probability leads to better energy efficiency performance. The intuitive explanation for this is that increasing the noise probability implies more energy can be harvested during the time τ. It is also interesting to observe that irrespective of the noise characteristics, the system becomes energy inefficient when τ is either too small or too large and that for each value of p there exists an optimal energy-harvesting time that maximizes the system performance. This is basically because when τ is too small, there is no sufficient time for energy harvesting. Hence, only a small amount of energy is harvested, which of course will result in poor spectral efficiency and then poor energy efficiency performance. At the other extreme, when τ is too large, too much energy will be harvested unnecessarily at the expense of information transmission time which, as a consequence, will also lead to poor energy efficiency. This phenomena is discussed below in more detail. It is important to state that the energy harvester efficiency also plays a major role in the energy efficiency performance of the proposed system.

B. Performance Optimization

We now consider the optimization problem of the energy-harvesting time factor in the DF-EH system. The optimal energy-harvesting time τ^* can be found as the solution of $\frac{\partial}{\partial \tau}\eta(\tau) = 0$. Although it is not easy to express this equation in closed form, it is straightforward to find its solution numerically using, for instance, the *FindMaximum* function in Mathematica. Substituting the resultant values of τ^* in (16) will give the maximum achievable energy efficiency of the proposed DF-EH system, which is presented in Fig. 4 as a function of the source-destination distance for different values of the idle power. For the sake of comparison, we also include results for the conventional DF relaying system and the DL approach. It should be noted that in this section we set $d_1 = d_0/3$, $d_2 = 2d_0/3$, SINR $= -30$ dB, $p = 0.01$, and from this point onward $\kappa = 1$. The first observation one can see from these results is the good match between the analytical and simulated results for the three systems. It is clear that the proposed approach always outperforms the conventional DF system irrespective of the system

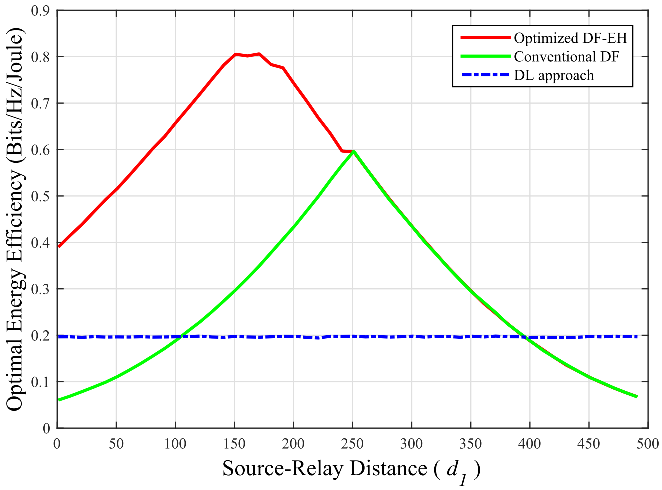

Fig. 5. Energy-efficiency performance as a function of the source-relay distance for the optimized DF-EH, conventional DF, and DL systems when $p = 0.1$.

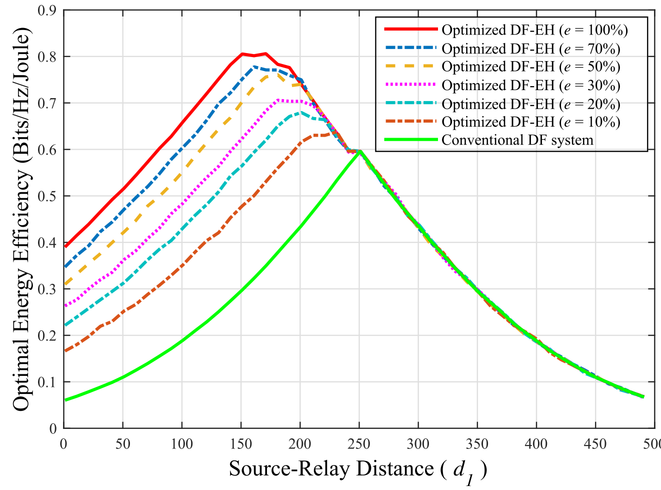

Fig. 6. Energy-efficiency performance versus the source-relay distance for the optimized DF-EH and conventional DF systems with various values of impulsive noise estimation accuracy when $p = 0.1$.

setup. It is also apparent that increasing the source-destination distance will worsen the energy efficiency performance of all systems and more so for the DL transmission which is intuitive. The other interesting observation one can notice from these results is that the DL system has better performance in comparison to the other two relaying systems when the distance is relatively small. This implies that using multiple PLC modems becomes energy inefficient in short-distance scenarios due to probably the increased idle power consumption. At the other extreme, when this distance is too large, all the systems yield poor performance meaning that more intermediate PLC modems should be deployed in such environments. The final remark on these results is that having PLC modems with lower idle power values can further improve the energy efficiency of PLC relaying systems.

C. Impact of Relay Location on the Optimized System

We now look into the impact of the relay location on the optimized DF-EH system and the conventional DF approach. To do this, we set $d_0 = 500\,\text{m}$ and vary d_1 from 0 to 500 while $d_2 = d_0 - d_1$ and plot in Fig. 5 the optimized energy efficiency performance with respect to d_1. A number of observations can be highlighted in this figure. For example, the optimized DF-EH approach is always able to outperform the conventional DF system if the relay is placed before the midpoint between the source and destination modems, in this case 30% improvement is attained; otherwise the two systems will perform similarly. This is because the overall performance of any DF-based relaying system is determined by the link with the lowest spectral efficiency, which is the source-relay link in this case when $d_1 > d_2$. Therefore, to more efficiently exploit the energy harvested at the relaying PLC modem, we should ensure that d_2 is always greater than d_1.

It is interesting to indicate that the optimal energy efficiency performance of the conventional DF system is symmetrical around the source-destination midpoint, which is not the case for the proposed DF-EH scheme. The reason for this is because the available transmit power at the source and relaying modems is equal in the conventional DF system. On the other hand, in the proposed EH-DF scheme, the relay transmit power is larger than the source's due to the extra energy harvested at the relay, and this yields the nonsymmetric performance in Fig. 5.

D. Impact of Impulsive Noise Estimation Accuracy

All the above results presented so far have assumed perfect detection of impulsive noise and hence they represent the maximum possible achievable gains. In practice, however, this is not always attainable. We therefore examine in this section the influence of impulsive noise estimation accuracy (e) on the performance of the proposed DF-EH system. To gain insights into this, we plot in Fig. 6 the energy efficiency performance with different noise estimation accuracies ranging from perfectly estimated to badly estimated, $e = 100\%$, 70%, 50%, 30%, 20% and 10%. It is worth noting that $e = 100\%$ represents perfect estimation of impulsive noise. It can be observed from this figure that the proposed approach is always able to outperform the conventional system even when the noise estimation accuracy is small and that this gain increases as the estimation becomes more accurate. For example, the achievable gains over the conventional system can be as high as 33%, 28%, 25%, 17%, 12%, and 5% when the noise estimation accuracy is 100%, 70%, 50%, 30%, 20%, and 10%, respectively. The other practical requirement of the proposed system is the extra hardware; more specifically, the energy-harvesting circuit. This circuit is however very simple and can be built using a few basic electronic components.

E. Average Outage Probability

In this section, we examine the average outage probability of energy efficiency by presenting some numerical examples of the expressions derived above along with simulation results. We plot this probability in Fig. 7 for the proposed DF-EH, conventional DF, and DL systems as a function of the energy

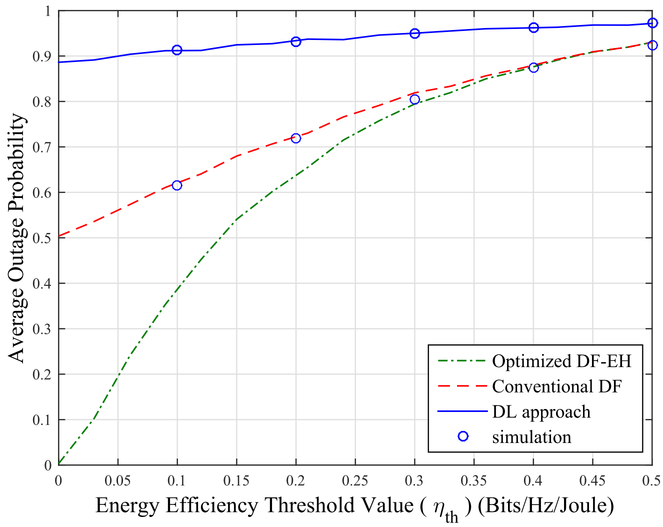

Fig. 7. Average outage probability performance of the energy efficiency for the DF-EH, conventional DF, and DL systems.

efficiency threshold $(\eta_{\rm th})$ for the following system parameters: $\mu_1 = \mu_2 = 3$ dB, $\sigma_1^2 = \sigma_2^2 = 3$ dB, $d_1 = 125$ m, $d_2 = 375$ m, $p = 0.01$, and SINR $= -20$ dB. The numerical results of the DF-EH, conventional DF, and DL systems are obtained from (36), (37), and (38), respectively. The good agreement between the analytical and simulated results clearly verifies the accuracy of our analysis. It is apparent from this figure that the proposed system always has the lowest outage probability for a given energy efficiency threshold in comparison to the other two systems. It should be noted that the results for the DF-EH system are found for the optimized system, i.e., the optimal energy-harvesting time κ^* is used in (36). In addition, as anticipated, the DL approach always has the worst outage probability performance.

F. Frequency Selection and Power Allocation

In the following, we look into the effect of the previously discussed frequency selection and power allocation schemes on the energy efficiency performance of the proposed system. The system parameters considered here are $d_0 = 200$ m, $d_1 = 75$ m and the number of cables is three. For these parameters, Fig. 8 depicts the energy efficiency performance for the DF-EH, conventional DF, and DL systems as a function of the average SNR with optimal frequency selection, random frequency selection, and equal power allocation. It is interesting to see that for all the systems considered, at low SNR, optimal frequency selection outperforms the equal power allocation scheme. This can be justified by the fact that when the signal power is relatively low, it becomes more efficient to allocate all the available power to one channel that has the best frequency. On the other hand, however, as the SNR becomes higher, equal power allocation offers better performance than optimal frequency since all channels can now be allocated sufficiently high power.

Furthermore, it is noticeable that random frequency selection always yields the worst performance over all the given SNR spectrum regardless of the system used. Nonetheless, this

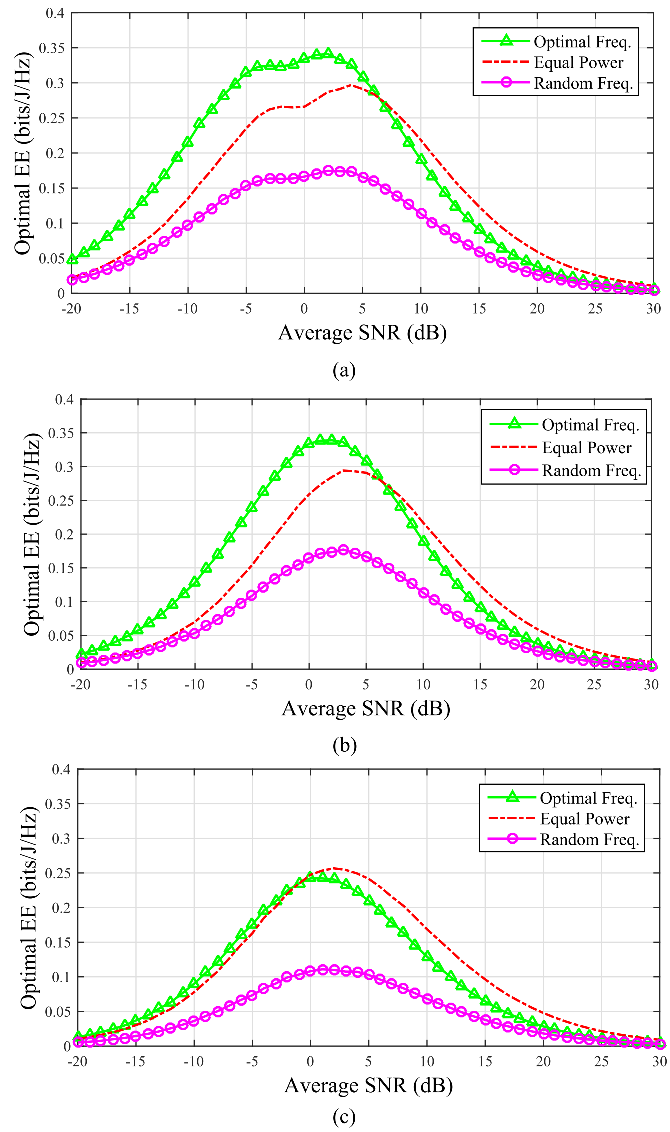

Fig. 8. Energy-efficiency performance versus the average SNR for the DF-EH, conventional DF, and DL systems with various power allocation strategies when $p = 0.01$. (a) DF-EH system. (b) Conventional DF system. (c) DL system.

scheme can still be very useful in applications where energy efficiency is not the main concern but rather more security concerned. In addition, when the average SNR is very large, the performance starts to decline for all the systems approaching zero; this is simply because the number of bits delivered per energy unit is fixed while increasing the transmit power. In such cases, adaptive bit loading should be exploited to improve the system's energy efficiency. Irrespective of the power allocation scheme deployed, it is clearly visible that the proposed DF-EH system always offers the best performance relative to the other two and that the DL exhibits the worst performance.

Finally, it should be stressed that the results for the optimal frequency selection scheme are obtained for perfectly known CSI. With imperfect knowledge of CSI, the systems performances above may differ and optimal frequency selection may no longer attain the best performance. This, however, can be further investigated in future work.

VIII. Conclusion

This paper studied the performance of a dual-hop DF relaying PLC system. To improve the energy efficiency of such systems, we proposed energy-harvesting at the relay, adopting the time-switching relaying protocol. To highlight the achievable gains, we also included the performance of the conventional DF and the DL systems. As such, accurate analytical expressions of the energy efficiency and closed-form expressions of the outage probability were derived for these systems. To further improve energy efficiency, we applied different frequency selection and power allocation strategies exploiting the multiple cables available in the power line network. It was shown that optimizing the energy-harvesting time is the key to achieve the best performance and that more than 30% of energy efficiency improvement can be obtained with the proposed system relative to the conventional DF relaying approach. For the attenuation model adopted in this paper, the energy-harvesting relaying modem should be placed before the source-destination midpoint for best performance. It was also presented that the optimized DF-EH system can significantly minimize the average outage probability compared to the conventional DF and DL schemes. In addition, frequency selection and power allocation can further enhance the energy efficiency of the proposed system. In particular, optimal frequency selection tends to have the best performance when SNR is relatively low, whereas when SNR is sufficiently large, equal power allocation becomes more appropriate.

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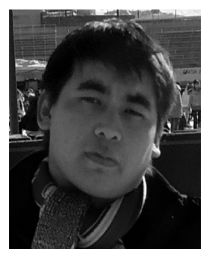

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