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Enhanced Amplify-and-Forward Relaying in Non-Gaussian PLC Networks

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ABSTRACT Relaying over power line communication (PLC) channels has the potential to improve the reliability and robustness of many PLC-based applications. In particular, this paper proposes to enhance the energy efficiency (EE) of a dual-hop relaying PLC system in the presence of impulsive noise by considering energy-harvesting (EH) at the relaying modem. Amplify-and-forward (AF) relaying and time-switching relaying EH protocols are deployed in this paper. The PLC modems are assumed to have the capability to go on low-power consumption sleep mode when they are neither transmitting nor receiving. The system performance is evaluated in terms of EE and average outage probability for which analytical expressions are derived. Using the derived expressions, several system parameters are investigated, such as the channel gain, which is related to the number of network branches, EH time factor and impulsive noise characteristics. Particularly, the optimization problem of the EH time is addressed thoroughly in order to maximize the achievable gains. Results reveal that the proposed system can offer considerable improvements compared with the conventional AF relaying scheme.

INDEX TERMS Amplify-and-forward (AF) relaying, energy efficiency (EE), energy-harvesting (EH), impulsive noise, power line communication (PLC).

I. INTRODUCTION

No doubt that the modern society's demand for electricity is rapidly increasing everyday. For instance, there are more than 15 Billion devices today on what is popularly referred to as the Internet of Things (IoT), and this number is expected to triple by 2020, according to Cisco statistics [1]. Such figures have driven utility companies and electricity suppliers to urgently modernize and revolutionize the existing and aging grid to meet this demand; this is more commonly referred to as *smart grid*. As such, reliable communication remains the most determinant factor for the efficient realization of smart grids which is widely agreed to be attainable with heterogeneous networks including, but not limited to, the power line communication (PLC) technology. The fact that this technology is a *through-grid* technology makes it a more attractive solution to smart grid developers allowing significant installation cost savings. Not only that, power line networks reaching every single building on the planet is another favorable feature making a wide range of applications feasible such as advanced metering, load control, dynamic pricing, fault detection, self-healing and monitoring applications [2], [3]. In general, PLC is divided into narrowband PLC [4], [5], and broadband PLC [6]–[8].

On the other hand, power lines are not a favorable medium for high-frequency communication signals [9]–[12]. Another burden of PLC technology is the low transmit power restrictions that should comply with national and international regulations [13]. Some examples here are the Federal Communications Commission (FCC) Part 15 (US), EN55022 Class B (European Union) and German Law NB30 (Germany) with the following transmit power spectral density (PSD) restrictions: −60 dBm/Hz, −67 dBm/Hz and −93 dBm/Hz, respectively [14]. As a consequence, the signal-to-noise ratio (SNR) at the receiving PLC modems can be very low which may significantly deteriorate the reliability of such links. To copy with this, different techniques have been reported in the literature including cooperative relaying.

In this respect, power consumption in relaying PLC networks has recently been investigated by several researchers [15]–[20]. Although these studies have considered many relaying scenarios and system configurations providing beneficial insights on different aspects, their focus is limited to only optimizing system parameters in order to reduce transmit power of PLC modems. Unlike the aforementioned works, in this paper we propose to harvest the undesirable energy of impulsive noise present over PLC channels to improve the energy efficiency (EE). Specifically, we consider dual-hop amplify-and-forward (AF) relaying equipped with an energy harvester; hence, the proposed scheme will be referred to as the AF-EH system. It is noteworthy that noise over PLC channels is always mitigated, see e.g., [10], [21]–[23] and the references therein; therefore, its energy would always be wasted. For the sake of comparison and for more quantitative characterization of the achievable gains, we also study the performance of the conventional dual-hop AF relaying PLC system. The system performance will be evaluated in terms of EE and average outage probability.

The contributions of this paper are as follows. First, accurate analytical expressions for the EE and average outage probability are derived for both the AF-EH and conventional AF relaying PLC systems. Second, we address the optimization problem of the EH time factor in the proposed AF-EH system to maximize the achievable gains. In addition, using the derived expressions, we will discuss the impact of different system parameters and noise characteristics on the two adopted performance metrics. The theoretical development and extensive computer simulation results presented in this paper clearly demonstrated the superiority of the proposed system over the conventional relaying approach. Results also reveal that the average outage probability can be further enhanced as the harvested energy of impulsive noise increases.

The rest of this paper is organized as follows. Section II presents the system model and discusses the adopted relaying and EH protocols. In Section III, we analyze the EE and average outage probability of both the proposed AF-EH and conventional relaying systems. Section IV presents and discusses some numerical and simulated results for the two systems under consideration. Finally, conclusions are drawn in Section V.

The following notations are used in this paper. We use $f_X(\cdot)$ and $F_X(\cdot)$ to represent the probability density function (PDF) and the cumulative distribution function (CDF) of the random variable (X), respectively. In addition, $\Psi_X(\cdot)$ is the moment generation function (MGF) of X, $\mathbb{E}\{\cdot\}$ is the expectation operator, $|\cdot|$ is the absolute value operator and $\mathrm{erf}(\cdot)$ is the error function.

II. SYSTEM MODEL

Consider an AF relaying PLC system with three modems: source, relay and destination as illustrated in Fig. 1. The AF relay is equipped with an energy harvester to harvest the noise energy over the PLC channel. It is worth noting that coupling circuits are required in order to inject the PLC signals to the power line network. We use h_1 and h_2 to denote the source-relay and relay-destination channel gains which follow

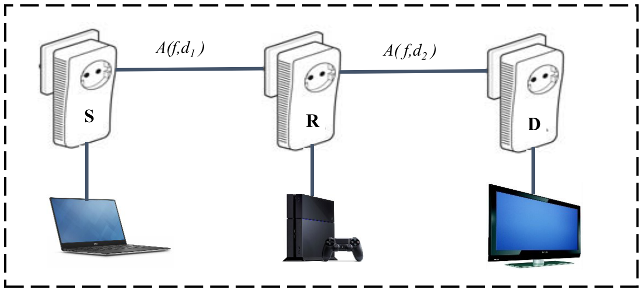

FIGURE 1. A diagram of the considered system.

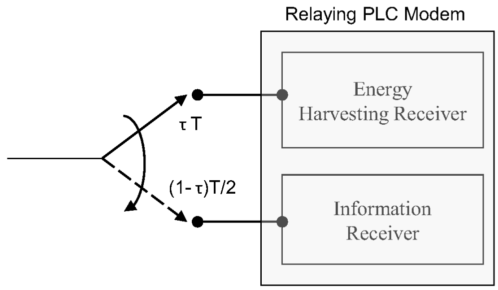

FIGURE 2. Relaying PLC modem based on TSR EH protocol.

log-normal distribution [11], [24], [25]. The cable attenuation and losses are represented by $A(d_i, f) = \exp(-\alpha d_i)$ where $i \in \{1, 2\}$, f denotes the operating frequency, α is the attenuation function and d_1 and d_2 are the source-relay and relay-destination distances, respectively.

The PLC noise at all modems is modeled using the Bernoulli-Gaussian noise model [26], which accounts for both background noise (n_w) and impulsive noise (n_i) with probability occurrence of p. Note that the two noise components are assumed to be independent since they have different origins in the PLC environment [27].

The relaying modem is based on time-switching relaying (TSR) EH protocol which is shown in Fig. 2. Based on this protocol, the EH time at the relay is τT, where $0 \leq \tau \leq 1$ is the EH time factor and T is the time required for transmitting one block from the source to the destination. The remaining time is used evenly for data transmission during phase I (source-to-relay) and phase II (relay-to-destination). Note that this study considers low data rate applications with delay-tolerance and aims to mainly improve EE; hence, throughput reduction due to EH can be accommodated. It is also important to stress that since the impulsive noise energy is very high (it can be as high as 50dB above the background level [28]), conventional energy conversion circuits can be used.

PLC modems can be in one of the following power modes: dynamic power (P_{dyn}), static power (P_{stc}) and idle power (P_{idl}) [19]. Assuming that all the modems have same power consumption properties,[1] the total energy consumption

[1] In most practical PLC setups, PLC modems from same manufactures are used, mostly identical, for better interoperability.

for the proposed AF-EH system, during phase I and phase II, can be given respectively as

$$E_{t,1}^{AF-EH} = \frac{(1-\tau)T}{2}\underbrace{\left(P_{dyn}+2P_{stc}+P_{idl}\right)}_{P_{t,1}^{AF-EH}}, \quad (1)$$

$$E_{t,2}^{AF-EH} = \frac{(1-\tau)T}{2}\underbrace{\left(G^2P_{dyn}+2P_{stc}+P_{idl}\right)}_{P_{t,2}^{AF-EH}}, \quad (2)$$

where G is the relay gain.

On the other hand, the total energy consumption for the conventional AF relaying system can be expressed as a function of the relay gain as

$$E_t^{AF} = \frac{T}{2}\underbrace{\left(P_{dyn}+2P_{stc}+P_{idl}\right)}_{P_{t,1}^{AF}} + \frac{T}{2}\underbrace{\left(G^2P_{dyn}+2P_{stc}+P_{idl}\right)}_{P_{t,2}^{AF}}, \quad (3)$$

where the first and second terms represent the energy consumption during phases I and II, respectively.

III. PERFORMANCE ANALYSIS

To start with, the received signal at the relaying modem in the first phase can be given by

$$y_r(t) = \sqrt{P_s}\exp(-\alpha d_1)h_1 s(t) + n_r(t), \quad (4)$$

where P_s is the source transmit power (i.e., the dynamic power of the source), $s(t)$ is the information signal normalized as $\mathbb{E}\left\{|s|^2\right\} = 1$ and $n_r(t)$ is the noise at the relay with variance σ_r^2. The harvested energy at the relay can then be written as

$$E_H = \kappa\tau T\sigma_r^2, \quad (5)$$

where $0 < \kappa < 1$ is the EH efficiency. In the second phase, the transmitted signal at the relay after the base-band processing and amplification can be expressed as

$$r(t) = \sqrt{P_s}\exp(-\alpha d_1)Gh_1 s(t) + Gn_r(t). \quad (6)$$

The received signal at the destination modem is

$$y_d(t) = \sqrt{P_sP_r}\exp(-\alpha(d_1+d_2))h_1h_2Gs(t) + \sqrt{P_r}\exp(-\alpha d_2)h_2Gn_r(t) + n_d(t), \quad (7)$$

where $n_d(t)$ is the noise at the destination modem, $P_r = P_{re} + P_{rh}$ is the total relay transmit power, P_{re} is the relay power from the external power source and P_{rh} is the harvested power which, using (5), can be written as

$$P_{rh} = \frac{2E_H}{(1-\tau)T} = \frac{2\kappa\tau}{(1-\tau)}\sigma_r^2. \quad (8)$$

Now, grouping the information and noise terms in (7), we can obtain the SNR at the destination modem as

$$\gamma_d = \frac{P_sP_r\exp(-2\alpha(d_1+d_2))G^2h_1^2h_2^2}{P_r\exp(-2\alpha d_2)\sigma_r^2G^2h_2^2+\sigma_d^2}. \quad (9)$$

For simplicity, equation (9) can also be re-expressed as

$$\gamma_d = \frac{ah_1^2h_2^2}{ch_2^2+b}, \quad (10)$$

where $a = P_sP_r\exp(-2\alpha(d_1+d_2))G^2$, $b = \sigma_d^2$ and $c = P_r\exp(-2\alpha d_2)\sigma_r^2G^2$.

A. ENERGY EFFICIENCY ANALYSIS

The EE (η), in bits/Hz/Joule, is given by the ratio of the average spectral efficiency (ξ) and the total power consumption (P_t). With this in mind, the EE can be calculated as

$$\eta = \frac{\mathbb{E}\{\xi\}}{P_t}, \quad (11)$$

where $P_t = P_{t,1}^{AF-EH} + P_{t,2}^{AF-EH}$ and $P_{t,1}^{AF-EH}$ and $P_{t,2}^{AF-EH}$ are defined in (1) and (2), respectively. The spectral efficiency, also referred to as bandwidth efficiency, is defined as the maximum amount of information transmitted per channel use (given in bits/s/Hz), is calculated for the proposed PLC system as

$$\xi = \frac{1-\tau}{2}\sum_{i=0}^{1}p_i\log_2(1+\gamma_i), \quad (12)$$

where $p_0 = 1-p$, $p_1 = p$, $\gamma_0 = \gamma_d$, $\gamma_1 = \gamma_d/\beta$, $\beta = 1+\sigma_i^2/\sigma_w^2$ and σ_w^2 and σ_i^2 denote the background and impulsive noise variances, respectively. Note that the term $(1-\tau)$ implies that only during this fraction of time information transmission takes place as the rest of the time is occupied for EH.

The average spectral efficiency can be determined as

$$\mathbb{E}\{\xi\} = \frac{1-\tau}{2}\sum_{i=0}^{1}p_i\int_0^\infty \log_2(1+x)f_{\gamma_i}(x)\,dx, \quad (13)$$

where $f_{\gamma_0}(\cdot)$ and $f_{\gamma_1}(\cdot)$ are the PDFs of γ_0 and γ_1, respectively.

Using the partial integration, we can also write (13) in the following form

$$\mathbb{E}\{\xi\} = \frac{1-\tau}{2\ln(2)}\sum_{i=0}^{1}p_i\int_0^\infty \frac{1-F_{\gamma_i}(v)}{1+v}\,dv, \quad (14)$$

where $F_{\gamma_0}(\cdot)$ and $F_{\gamma_1}(\cdot)$ are the CDFs of γ_0 and γ_1, respectively.

Now, using (10) and substituting $X = h_1^2$ and $Y = h_2^2$, we calculate $F_{\gamma_0}(v)$ as

$$F_{\gamma_0}(v) = \Pr\left\{\frac{aXY}{cY+b} < v\right\} = \Pr\left\{Y < \frac{bv}{aX-cv}\right\}. \quad (15)$$

Considering the fact that X is always a positive value, we can write (15) as

$$F_{\gamma_0}(v)=\begin{cases}\Pr\left\{Y<\dfrac{bv}{aX-cv}\right\}, & X<\dfrac{cv}{a}\\ \Pr\left\{Y>\dfrac{bv}{aX-cv}\right\}=1. & X>\dfrac{cv}{a}\end{cases} \quad (16)$$

Using this definition, $F_{\gamma_0}(v)$ can therefore be calculated as

$$F_{\gamma_0}(v)=\int_0^{\frac{cv}{a}} f_X(z)\underbrace{\Pr\left\{Y>\frac{bv}{az-cv}\right\}}_{=1}\mathrm{d}z + \int_{\frac{cv}{a}}^{\infty} f_X(z)\Pr\left\{Y\le\frac{bv}{az-cv}\right\}\mathrm{d}z, \quad (17)$$

which can also be reduced to

$$F_{\gamma_0}(v)=\int_0^{\frac{cv}{a}} f_X(z)\,\mathrm{d}z+\int_{\frac{cv}{a}}^{\infty} f_X(z)\,F_Y(\Xi)\,\mathrm{d}z, \quad (18)$$

where

$$f_X(z)=\frac{\zeta}{z\sqrt{8\pi\sigma_{h_1}^2}}\exp\left(-\frac{\left(\zeta\ln(z)-2\mu_{h_1}-\zeta\ln(a)\right)^2}{8\sigma_{h_1}^2}\right), \quad (19)$$

and

$$F_Y(\Xi)=\frac{1}{2}+\frac{1}{2}\mathrm{erf}\left(\frac{\zeta\ln(\Xi)-2\mu_{h_2}}{\sqrt{8}\sigma_{h_2}}\right), \quad (20)$$

where $\zeta=10/\ln(10)$ is a scaling constant, $\Xi=\frac{bv}{az-cv}$, μ_{h_i} and $\sigma_{h_i}^2$ (both in decibels) are the mean and the variance of $10\log_{10}(h_i)$, respectively, $i\in\{1,2\}$.

Substituting (19) and (20) into (18) yields $F_{\gamma_0}(v)$. Following the same procedure, we can also derive $F_{\gamma_1}(v)$. Finally, substituting $F_{\gamma_0}(v)$ and $F_{\gamma_1}(v)$ into (14) gives

$$\mathbb{E}\{\xi\}=\frac{(1-\tau)\zeta}{\sqrt{512\pi\sigma_{h_1}^2}\ln(2)}\sum_{i=0}^{1}p_i\int_0^{\infty}\frac{1}{1+v}\times\int_{\Lambda_i}^{\infty}\frac{1}{z}\left(1+\mathrm{erf}\left(\frac{\zeta\ln(\Xi_i)-2\mu_{h_2}}{\sqrt{8}\sigma_{h_2}}\right)\right)\times\exp\left(-\frac{\left(\zeta\ln(z)-\left(2\mu_{h_1}+\zeta\ln(a)\right)\right)^2}{8\sigma_{h_1}^2}\right)\mathrm{d}z\mathrm{d}v \quad (21)$$

where $\Lambda_0=\frac{cv}{a}$, $\Lambda_1=\Lambda_0\beta$, $\Xi_0=\frac{bv}{az-cv}$ and $\Xi_1=\frac{bv\beta}{az-cv\beta}$. Finally, using (11) and (21), we obtain the EE of the proposed system.

Another approach to determine $\mathbb{E}\{\xi\}$ is based on using the useful lemma presented in [29]. Using (10) and (12) while substituting $\mathcal{X}=aX$, $\mathcal{Z}_0=bZ+c$, $\mathcal{Z}_1=(bZ+c)\beta$ and $Z=h_2^{-2}$, $\mathbb{E}\{\xi\}$ can be written as

$$\mathbb{E}\{\xi\}=\frac{(1-\tau)}{2}\sum_{i=0}^{1}p_i\mathbb{E}\left\{\log_2\left(1+\frac{\mathcal{X}}{\mathcal{Z}_i}\right)\right\}. \quad (22)$$

Based on [29, eq. (3)], we can calculate (22) as

$$\mathbb{E}\{\xi\}=\frac{1-\tau}{2\ln(2)}\sum_{i=0}^{1}\int_0^{\infty}\frac{p_i}{s}\left(1-\Psi_{\mathcal{X}}(s)\right)\Psi_{\mathcal{Z}_i}(s)\,\mathrm{d}s \quad (23)$$

where $\Psi_{\mathcal{X}}(s)$, $\Psi_{\mathcal{Z}_0}(s)$ and $\Psi_{\mathcal{Z}_1}(s)$ are the MGFs of $\mathcal{X}$, $\mathcal{Z}_0$ and $\mathcal{Z}_1$, respectively. With the help of the series expansion based on Gauss-Hermite integration, we can write these MGFs as follows [30]–[32]

$$\Psi_{\mathcal{X}}(s)\triangleq\sum_{n=1}^{N}\frac{w_n}{\sqrt{\pi}}\exp\left(-as\exp\left(\frac{\sqrt{8}\sigma_{h_1}x_n+2\mu_{h_1}}{\zeta}\right)\right) \quad (24)$$

$$\Psi_{\mathcal{Z}_i}(s)\triangleq\exp(-\Gamma_i s)\sum_{n=1}^{N}\frac{w_n}{\sqrt{\pi}}\times\exp\left(-\Delta_i s\exp\left(-\frac{\sqrt{8}\sigma_{h_2}x_n+2\mu_{h_2}}{\zeta}\right)\right) \quad (25)$$

where $\Gamma_0=c$, $\Gamma_1=c\beta$, $\Delta_0=b$ and $\Delta_1=b\beta$. In addition, N is the Hermite integration order, $\{w_n\}_{n=1}^{N}$ and $\{x_n\}_{n=1}^{N}$ are the weights and abscissas, respectively, which can be found in [33, Table 25.10]. Note that $N=25$ will be used in all our evaluations in this paper. Now, substituting (23) into (11) yields the EE of the proposed system.[2]

Following the same procedure as above while setting $P_{rh}=0$, $\tau=0$ and using (3) instead of (1) and (2), we can obtain the EE expression for the conventional AF system. For brevity, this derivation is omitted in this work.

B. AVERAGE OUTAGE PROBABILITY ANALYSIS

The outage probability is defined as the probability that the instantaneous EE falls below a certain threshold value (η_{th}) and is expressed as

$$\mathcal{O}(\eta_{th})=\Pr\{\eta<\eta_{th}\}. \quad (26)$$

Using (10)-(12), we can rewrite (26) as

$$\mathcal{O}(\eta_{th})=\Pr\left\{(1-p)\log_2\left(1+\frac{aXY}{cY+b}\right)+p\log_2\left(1+\frac{aXY}{(cY+b)\beta}\right)<v\right\}, \quad (27)$$

where $v=\frac{2\eta_{th}P_t}{(1-\tau)}$. To simplify our analysis, we use the high SNR approximation; that is, (27) becomes [35]

$$\mathcal{O}^H(\eta_{th})\simeq\Pr\left\{\left(\frac{aXY}{cY+b}\right)^{1-p}\left(\frac{aXY}{(cY+b)\beta}\right)^{p}<2^v\right\} \quad (28)$$

[2]For more details, the reader may refer to [34] for the EE analysis of the ideal-relaying EH PLC system.

which, after some basic algebraic manipulations, can be further simplified to

$$\mathcal{O}^H(\eta_{th}) \simeq \Pr\left\{\left(\frac{aXY}{cY+b}\right)\frac{1}{\beta^p} < 2^v\right\}$$
$$\simeq \Pr\left\{Y < \frac{\beta^p 2^v b}{(aX-\beta^p 2^v c)}\right\}, \quad (29)$$

which can also be given by

$$\mathcal{O}^H(\eta_{th}) \simeq \begin{cases} \Pr\left\{Y < \dfrac{\beta^p 2^v b}{aX-\beta^p 2^v c}\right\}, & X < \dfrac{\beta^p 2^v c}{a} \\ \Pr\left\{Y > \dfrac{\beta^p 2^v b}{aX-\beta^p 2^v c}\right\} = 1. & X > \dfrac{\beta^p 2^v c}{a} \end{cases} \quad (30)$$

Using this definition, and similar to the derivation in the previous section, the outage probability can be calculated as

$$\mathcal{O}^H(\eta_{th}) \simeq \int_0^{\frac{\beta^p 2^v c}{a}} f_X(z)\,\mathrm{d}z + \int_{\frac{\beta^p 2^v c}{a}}^{\infty} f_X(z) F_Y(\Upsilon)\,\mathrm{d}z, \quad (31)$$

where

$$f_X(z) = \frac{\zeta}{z\sqrt{8\pi\sigma_{h_1}^2}}\exp\left(-\frac{(\zeta\ln(z)-2\mu_{h_1}-\zeta\ln(a))^2}{8\sigma_{h_1}^2}\right), \quad (32)$$

$$F_Y(\Upsilon) = \frac{1}{2}+\frac{1}{2}\,\mathrm{erf}\left(\frac{\zeta\ln(\Upsilon)-2\mu_{h_2}}{\sqrt{8}\sigma_{h_2}}\right), \quad (33)$$

and $\Upsilon = \frac{\beta^p 2^v c_2}{az-\beta^p 2^v c}$.

Finally, substituting (32) and (33) into (31) yields the system's average outage probability given by

$$\mathcal{O}^H(\eta_{th}) \simeq 1 - \frac{\zeta}{\sqrt{128\pi\sigma_{h_1}^2}}\int_{\frac{\beta^p 2^v c}{a}}^{\infty}\frac{1}{z} \times \left(1+\mathrm{erf}\left(\frac{\zeta\ln(\Upsilon)-2\mu_{h_2}}{\sqrt{8}\sigma_{h_2}}\right)\right) \times \exp\left(-\frac{(\zeta\ln(z)-2\mu_{h_1}-\zeta\ln(a))^2}{8\sigma_{h_1}^2}\right)\mathrm{d}z. \quad (34)$$

The average outage probability analysis of the conventional AF relaying system is omitted here since it can be straightforwardly obtained from (34) by substituting $P_{rh}=0$ and $\tau=0$.

IV. RESULTS AND DISCUSSIONS

In the following, we present some numerical examples for the derived EE and average outage probability expressions in different channel and noise scenarios. For fair comparison, same noise and channel characteristics will be used in both the proposed and conventional relaying systems. In addition, the source and relay power consumption sources (including transmit powers) are assumed to be equal in the two systems. For the cable attenuation model, we use $\alpha = a_o + a_1 f^k$ where $a_o = 9.4\times10^{-3}$ and $a_1 = 4.2\times10^{-7}$ are constants determined from measurements, $k = 0.7$ is the exponent of the attenuation factor and $f = 30$ MHz [9]. Monte Carlo simulations are also conducted to assess the accuracy of the derived expressions in which results are averaged over 10^6 independent channel realizations, i.e., based on 10^6 iterations.

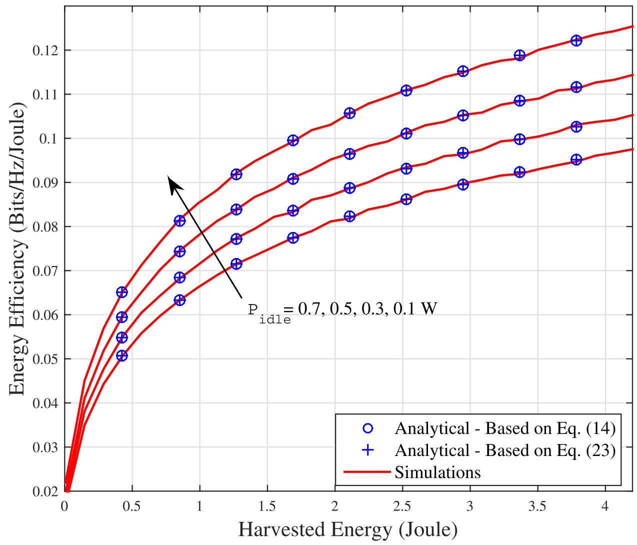

FIGURE 3. EE performance of the proposed AF-EH system with respect to the harvested energy for different values of P_{idle} when $\tau = 0.7$.

A. ENERGY EFFICIENCY PERFORMANCE

If not specified, the system parameters used in this section are: $P_s = 1$W, $P_{stc} = 0.7$W, $P_{idl} = 0.1$W, $P_{re} = 0.2$W, $G = 1$, $\kappa = 1$, $\mu_{h_1} = \mu_{h_2} = 2$dB, $\sigma_{h_1}^2 = \sigma_{h_2}^2 = 5$dB, $d_1 = 200$ m, $d_2 = 300$ m, $p = 0.01$ and signal-to-impulsive noise ratio (SINR) $= -20$dB.

1) IMPACT OF HARVESTED ENERGY AND IDLE POWER

To begin with, we plot in Fig. 3 the analytical and simulated EE performance of the AF-EH system versus the harvested energy for different values of P_{idle} when $\tau = 0.7$. Clearly, the analytical and simulated results are in good agreement which verifies the accuracy of our analysis. It can be seen from these results that the EE performance enhances as the amount of the harvested energy increases irrespective of the modem's idle power. It is also noticeable that as the idle power consumption increases, the system becomes less energy efficient.

2) EH TIME FACTOR AND EH EFFICIENCY

The EH time is a key parameter in designing the proposed system; hence, a good understanding of this parameter is crucial. As such, we plot in Fig. 4 the EE of the AF-EH system as a function of the EH time factor for several values

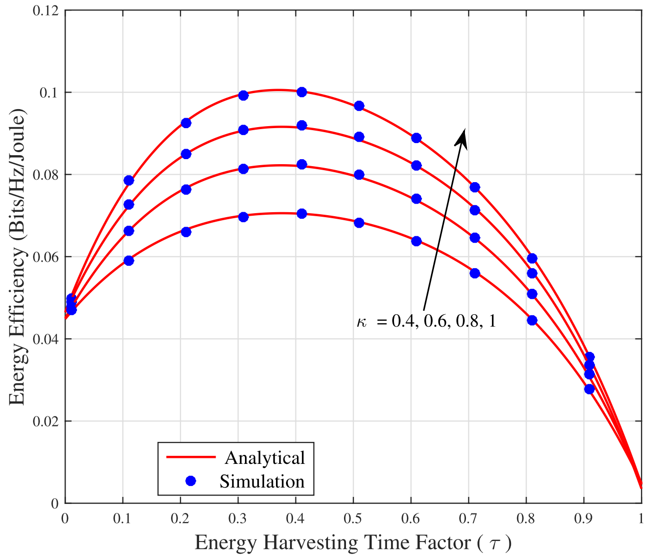

FIGURE 4. EE performance of the proposed AF-EH system versus the EH time factor for several values of κ when $P_{re} = 0.1$W.

of κ. Having a closer look at this figure, it can be seen that a careful selection of the EH time factor is vital to maximize the system performance since a too low or a too large value of this parameter can significantly deteriorate performance. Another remark on the results in Fig. 4 is that reducing the efficiency of the energy harvester will negatively impact the EE performance. The optimization problem of the EH time factor is thoroughly investigated below.

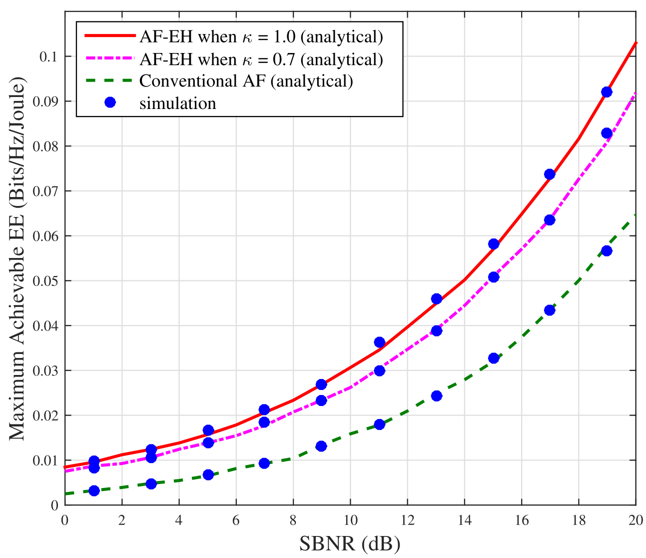

FIGURE 5. Maximum achievable EE performance of the AF-EH and conventional AF relaying systems versus the SBNR with different values of κ.

3) PERFORMANCE OPTIMIZATION

Now, we attempt to find the maximum achievable EE performance of the proposed system that corresponds to the optimal EH time factor. In light of this, we present in Fig. 5 some numerical examples of the maximum achievable EE as a function of the signal-to-background noise ratio (SBNR) for different values of κ. To highlight the achievable gains of the proposed system, we include in this figure results for the conventional AF relaying approach. The first observation one can see is that the proposed AF-EH system is always more energy efficient than the conventional scheme. It is also visible that decreasing the efficiency of the energy harvester will make the achievable gains less significant since less energy is now harvested at the relay; however, interestingly enough, even with only 70% EH efficiency, the proposed system is still able to outperform the conventional approach. In addition, for the two systems under consideration, increasing the SBNR makes these systems more energy efficient. For instance, at SBNR = 8dB, the EEs of the AF-EH and conventional AF systems are 0.02 and 0.01 bits/Hz/Joule, respectively, whereas at SBNR = 18dB these numbers increase to up to 0.08 and 0.05 bits/Hz/Joule, respectively.

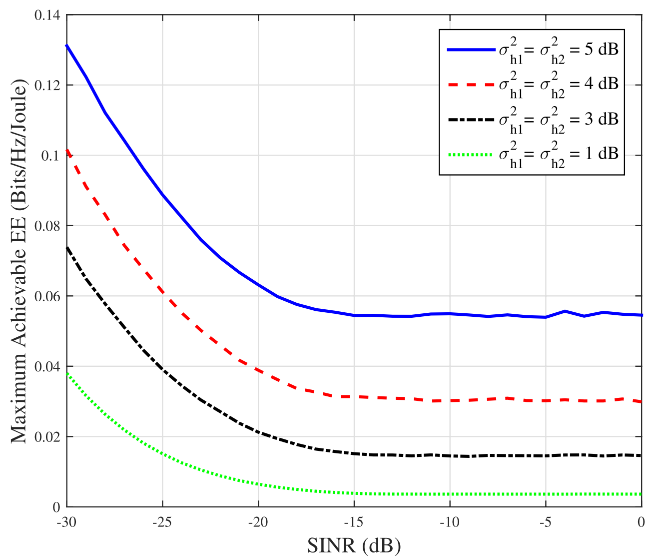

FIGURE 6. Maximum achievable EE performance of the AF-EH relaying system with respect to SINR when SBNR = 20dB, $\sigma^2_{h_1} = \sigma^2_{h_2}$ = 5dB, 4dB, 3dB and 1dB.

Furthermore, to illustrate the influence of the channel gains and SINR on the performance of the optimized AF-EH system, we plot in Fig. 6 the maximum achievable EE versus SINR for $\sigma^2_{h_1} = \sigma^2_{h_2}$ = 5dB, 4dB, 3dB and 1dB when SBNR = 20dB. Clearly, the optimized system becomes more energy efficient as the channel variances are increased. It is also evident that as SINR becomes small, i.e., the noise becomes more impulsive, the performance enhances. This is because of the fact that as the noise power increases, more energy can be harvested using the energy harvester at the relaying modem, which consequently makes the system more energy efficient. Additionally, it is interesting to note that the EE levels off when SINR goes beyond −20dB regardless of the channel gain value.

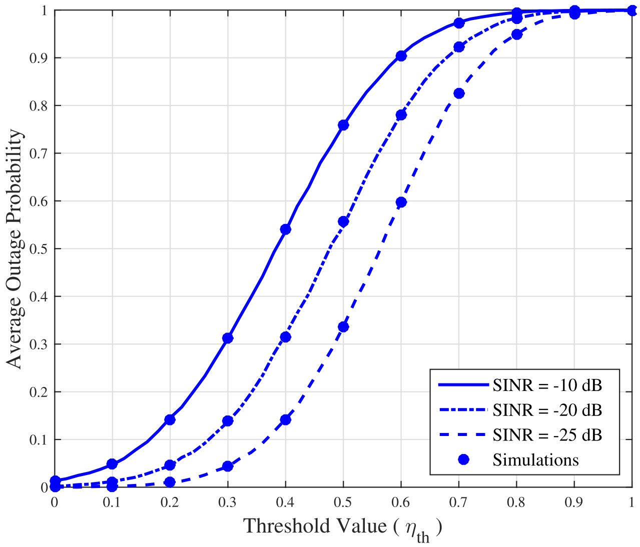

FIGURE 7. Average outage probability for the proposed AF-EH system with different SINR values when $p = 0.01$. Note that solid, dashed and dash-dotted lines represent the analytical results obtained from (34).

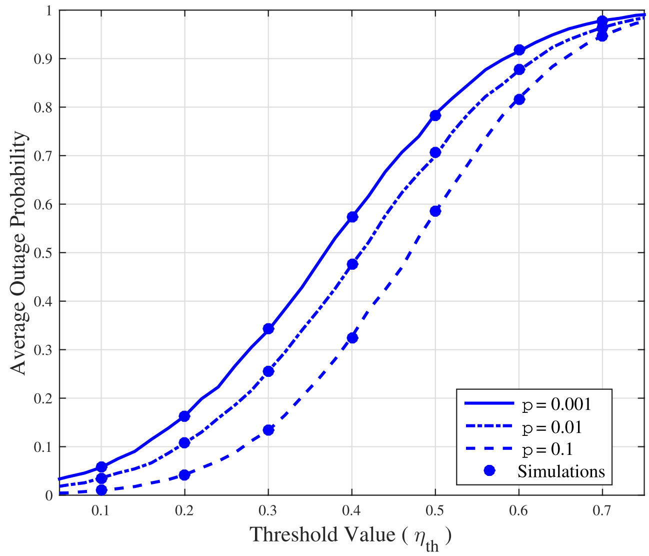

FIGURE 8. Average outage probability for the proposed AF-EH system with various impulsive noise probabilities when $\mathrm{SINR} = -20$ dB. Note that solid, dashed and dash-dotted lines represent the analytical results obtained from (34).

B. AVERAGE OUTAGE PROBABILITY PERFORMANCE

In this section, we examine the outage probability performance in various noise environments. The system parameters used here are SBNR $= 20$dB, $d_1 = d_2 = 30$ m, $P_{stc} = 0.6$W, $P_{idl} = 0.1$W, $\kappa = 1$, $\tau = 0.5$, $\mu_{h_1} = \mu_{h_2} = 3$dB and $\sigma^2_{h_1} = \sigma^2_{h_2} = 2$dB.

To begin with, we show in Fig. 7 the average outage probability performance with respect to the threshold value for several SINR values; specifically, we consider SINR $= -10$dB, -20dB and -25dB which represent a wide range of impulsive noise environments. Note that the transmit PSD is chosen in accordance to the FCC Part 15 standard, i.e., -60dBm/Hz[3] [36]. It is visible from this figure that the analytical results closely match the simulated ones. It is also apparent that as SINR increases, the outage probability improves. For instance, for a given threshold, e.g., 0.6 bit/Hz/Joule, the probability is 0.9 when SINR $= -10$dB and this probability goes down to 0.6 when SINR $= -25$dB. Additionally, when the threshold is too high, the outage performance becomes very high irrespective of the SINR value. The second set of the probability results is shown in Fig. 8. This figure demonstrates the outage probability versus the EE threshold for different impulsive noise probabilities. Note that the transmit PSD is again set at -60dBm/Hz. It is clear that the performance enhances as the noise probability becomes higher. This is due to the fact that higher noise probability of occurrence implies that more energy can be harvested at the relay during the allocated EH time which consequently leads to better EE at the destination modem; hence, the outage probability is reduced.

It is worthy pointing out that the performance can be further enhanced if the multiple power cables are exploited to create diversity which will allow using some frequency selection and power allocation schemes; more details can be found in [37].

[3]Since the frequency band used in this work is 30MHz, the transmit power can be determined as: PSD $+ 10\log(30 \times 10^6)$dBm.

V. CONCLUSION

This paper explored the performance of AF relaying PLC systems equipped with TSR-based EH. Accurate analytical expressions for the EE and average outage probability were derived. The influence of various system parameters on the aforementioned performance metrics were investigated and interesting findings were presented. It was shown that equipping PLC modems with EH capabilities can remarkably improve the EE performance compared to conventional relaying PLC systems. Besides, results also revealed that optimizing the EH time factor is a key factor to maximize the system performance and that as the noise becomes more impulsive, more energy will be harvested and therefore the outage probability will be further minimized.

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