The Performance of DF Relaying System Based on Energy Harvesting and Dual-Media Channels

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Abstract. In recent years, energy efficiency in multi-hop cooperative powerline communication (PLC) and wireless systems has recently received considerable attention. This paper considers the dual-hop PLC/wireless parallel communication system based on decode and forward (DF), where the relay harvests the high noise inherent in PLC channels to further enhance energy efficiency. In this paper, we derive the exact analytic expression of energy efficiency and the closed expression of outage probability. In order to compare and highlight the achievable gain, we also analyzed the related performances of DF relaying PLC system with energy harvesting (DF-EH). Then based on the theoretical calculation and simulation results, the influence of energy-harvesting time factor and other parameters on the system performance is analyzed. The result shows that energy-harvesting time factor and power allocation are the key factors affecting system performance. Relevant conclusions provide necessary theoretical support for the application of energy harvest technology in mixed media cooperative communication.

Keywords: Decode and forward · Energy harvesting · Outage probability · Energy efficiency

1 Introduction

Smart-grid techniques have attracted growing attention in recent years due to their inherent capacity to realize future energy-management system [1]. Power line communication has been deployed in the existing network structure [2, 3], where no new circuit installation is required and the construction cost is low. And wireless communication has the advantages of access flexible and simple networking, therefore, wireless relay technology has been widely used in the transmission field with wide coverage, and maintains good communication link quality in the PLC network.

To enhance robustness and link quality, a PLC network can collaborate with wireless network. Literature [4] and [5] put forward a new communication architecture, which allows signals to be transmitted simultaneously on PLC and wireless channels. The results show that the cooperation between PLC and wireless networks can ensure good communication quality and reduce the bit error rate and outage probability of the system. The study in [6] also presents a hybrid architecture of wireless and PLC

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networks which has been installed in rural and sparsely populated environments to provide broadband services and smart-grid services. Leonardo et al. [7] analyzed contrastively the characteristics and advantages of PLC/wireless hybrid data communication technology in smart grid and IoT. The results show that the mixed data communication method can effectively improve the performance of the system.

Very recently, power consumption in multi-hop PLC systems has attracted a large amount of research attention. For instance, D'Alessandro et al. proposed opportunistic decode and forward (ODF) and opportunistic amplify and forward (OAF) relaying for PLC systems [8, 9]. The authors showed that the scheme can effectively reduce transmission power. But that the two studies above considered only minimizing the transmit power of PLC modems. All the aforementioned studies have focused on only optimizing system parameters to reduce transmit power of PLC modems. In contrast, in reference [10], it is proposed for the first time to harvest energy of impulsive noise present over PLC channels and then forward the source signal with it to improve the energy efficiency of PLC systems. In the latest study, the author proposed a dual-hop PLC system based with energy harvesting (DF-EH) [11], and derived the analytical expressions of energy efficiency and outage probability. However, this paper only considers the PLC transmission medium, which has poor reliability.

In this paper, we present a PLC/Wireless parallel DF system based on energy harvesting (P/W-DF-EH). Firstly, we derive accurate analytical expressions for the energy efficiency (EE) and average outage probability of P/W-DF-EH and DF-EH systems, which are then validated with Monte Carlo simulations. Secondly, the effects of energy-harvesting time factor and impulse noise parameters on energy efficiency of the system are studied. Finally, a feasible scheme is proposed to balance the reliability and effectiveness of the system.

2 System Model

The model of PLC/W-DF-EH and DF-EH systems are shown in Fig. 1, which consists of source (S), relay (R) and destination (D). Relay installing Energy Harvesting (EH) device collects the inherent high noise energy in a PLC channel.

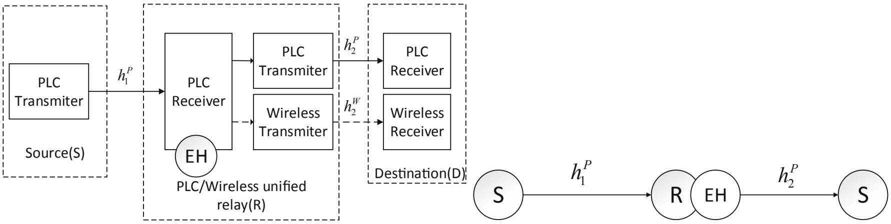

Fig. 1. System model for PLC/wireless-DF-EH and DF-EH system.

In the first time slot, the signal received by the power-line at the relay is given as:

$$y_r = \sqrt{P_s} h_1^P x_s + n_r^P \tag{1}$$

where P_s and x_s is the source transmit power and information signal normalized as $E\left\{|x_s|^2\right\} = 1$, and $\mathrm{n_r^P}$ is the PLC noise signal with variance N_{Pl}. h_1^P is the PLC channel fading coefficient, following the Lognormal (LogN) [12] with a probability density function (PDF) is:

$$f_{h_n^P} = \frac{\varsigma}{\sqrt{2\pi}\sigma_P Z} exp\left[-\frac{(10log_{10}(z) - \mu_P)^2}{2\sigma_P^2}\right], n \in \{1, 2\} \tag{2}$$

where $\varsigma = 10/ln\,10$ is a scaling constant, μ_P and σ_P^2 are the mean and the variance of $10log_{10}\left(h_n^P\right)$, respectively, the fading envelope is normalized, making $E[(h_n^P)^2] = exp\left(2\mu_P + 2\sigma_P^2\right) = 1$, namely $\mu_P = -\sigma_P^2$.

In the energy-harvesting part, we adopt the time-switching relaying energy-harvesting protocol. The total time needed to transmit information is T, and the EH time in the relay is defined as τT, where $0 \le \tau \le 1$ being the energy-harvesting time factor. The energy harvested by relay is $E_H = \kappa\tau T N_{Pl}$, where $0 < \kappa < 1$ is the energy-harvesting efficiency determined by the circuitry of the energy harvester at R.

In the second time slot, relay R with power P_r will transmit the signal x_r to D, then the signals received at node D are respectively:

$$y_d^P = \sqrt{\rho P_r} h_2^P x_r + n_d^P \tag{3a}$$

$$y_d^W = \sqrt{(1-\rho)P_r} h_2^W x_r + n_d^W \tag{3b}$$

where n_d^w is the noise signal of wireless at D with variance N_W, h_2^W is the wireless channel fading coefficient, following the Nakagami distribution with a PDF is:

$$f_{h_2^W}(z) = \frac{2}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^m z^{2m-1} exp\left(-\frac{mz^2}{\Omega}\right) \tag{4}$$

where $m \ge 0.5$ is Nakagami parameter, $\Omega = E[(h_2^W)^2]$, to be normalized $\Omega = 1$, then $\left(h_2^W\right)^2$ following the Gamma distribution $G(m, \Omega/m)$.

3 Performance Analysis

3.1 System Energy Efficiency

The total transmitted power of the relay is $P_r = P_{rh} + P_{re}$, where P_{re} is the power provided by the external power at the relay, and P_{rh} is the power harvested by the relay, as shown in [11]:

$$P_{rh} = \frac{E_H}{(1-\tau)T/2} = \frac{\tau}{(1-\tau)} 2\kappa N_{Pl} \tag{5}$$

Maximal Ratio Combining (MRC) is used at the destination. The signal-noise ratio (SNR) of relay $\mathrm{R}(\gamma_r)$ and the SNR of target node $\mathrm{D}(\gamma_d)$ can be obtained as $\gamma_r = P_s\left(h_1^P\right)^2/N_{pl}$ and $\gamma_d = \rho P_r\left(h_2^P\right)^2/N_{Pl} + (1-\rho)P_r\left(h_2^W\right)^2/N_W$.

The Energy Efficiency (EE, η) of the dual-hop DF system is the minimum EE of the SR and RD links. The EE is defined as the ratio of spectral efficiency (ξ) to transmitted power. Then the EE of R and D is respectively:

$$\eta_r = \xi_r/P_{t,1}^{P/W-DF-EH}, \eta_d = \xi_d/P_{t,2}^{P/W-DF-EH} \tag{6}$$

Referencing [11], we can write the total energy consumption for the proposed system during phase I and phase II, respectively, as

$$E_{t,1}^{P/W-DF-EH} = \frac{(1-\tau)T}{2}\left(P_{dyn} + 2P_{stc} + 2P_{idl}\right) \tag{7a}$$

$$E_{t,2}^{P/W-DF-EH} = \frac{(1-\tau)T}{2}\left(P_{dyn} + 3P_{stc} + P_{idl}\right) \tag{7b}$$

where P_{dyn} is dynamic power, P_{stc} is static power and P_{idl} is idle power.

The PLC noise is modeled as the Bernoulli–Gaussian noise model, where the probability of impulse noise is p. Therefore, the total noise power is $N_{Pl} = N_G + pN_I$, where N_G and N_I are the variance of background noise and impulse noise respectively. For non-Gaussian impulsive noise channels, the instantaneous spectral efficiency is determined as $\xi_i = p_0 log_2\left(1+\gamma_{j,0}\right) + p_1 log_2\left(1+\gamma_{j,1}\right), i \in \{r,d\}$, where $\gamma_{i,0}$ and $\gamma_{i,1}$ are the SNR of the receiver when probability is $p_0 = 1 - p$ and $p_1 = p$. In order to obtain the end-to-end Energy Efficiency of the P/W-DF-EH system, we first need to derive the EE for the SR and RD links as follows.

(a) SR link: the average spectral efficiency of SR link can be expressed as

$$\xi_r = \frac{(1-\tau)}{2}\sum\nolimits_{j=0}^{1} p_j \int_0^\infty log_2(1+\gamma) f_{\gamma_{r,j}}(\gamma) d\gamma \tag{8}$$

where $f_{\gamma_{r,0}}(\cdot)$ and $f_{\gamma_{r,1}}(\cdot)$ are the PDFs of $\gamma_{r,0}$ and $\gamma_{r,1}$, respectively, $\gamma_{r,0} = P_s\left(h_1^P\right)^2/N_G$, $\gamma_{r,1} = \mathrm{P_s}\left(\mathrm{h_1^P}\right)^2/(\mathrm{N_G}+\mathrm{N_I})$. Considering the SNR obey the LogN, the PDF of $\gamma_{r,j}$ can be expressed as:

$$f_{\gamma_{r,j}}(\gamma) = \frac{\varsigma}{\gamma\sqrt{8\pi}\sigma_P} exp\left[-\frac{\left(\varsigma\ \ln(\gamma) - \left(2\mu_P + \varsigma\ \ln\left(a_j\right)\right)\right)^2}{8\sigma_P^2}\right], j \in \{0,1\} \tag{9}$$

where $a_0 = P_s/N_G$, $a_1 = P_s/(N_G + N_I)$. We use the Hermite-Gauss quadrative method to obtain the approximate analytical expression of (8). To do this, we first let $x = \varsigma\ \ln(\gamma) - 2\mu_P - \varsigma\, ln\left(a_j\right)/\sqrt{8\sigma_P^2}$, we can get:

$$\xi_r = \frac{(1-\tau)}{2}\sum\nolimits_{j=0}^{1}\int_{-\infty}^{\infty}\frac{p_j}{\sqrt{\pi}}h(x)exp\left[-x^2\right]dx \tag{10}$$

Average spectral efficiency of the relay can consequently be calculated as

$$\xi_r \simeq \frac{(1-\tau)}{2}\sum\nolimits_{j=0}^{1}\sum\nolimits_{n=1}^{N}\frac{p_j}{\sqrt{\pi}}w_n h(x_n) \tag{11}$$

where $h(x_n) = log_2(1 + exp[\frac{\sqrt{8}\sigma_P x_n + 2\mu_P + \varsigma\, ln\left(a_j\right)}{\varsigma}])$, $\{w_n\}_{n=1}^{N}$ and $\{x_n\}_{n=1}^{N}$ are the weights and abscissas of the N-point Hermite–Gauss quadrature. According to Eqs. (7a) and (11), the EE of the relay is

$$\begin{aligned}\eta_r = {} & \frac{(1-\tau)}{2\left(P_{dyn} + 2P_{stc} + 2P_{idl}\right)} \\ & \times \sum\nolimits_{j=0}^{1}\sum\nolimits_{n=1}^{N}\left\{\frac{p_j w_n}{\sqrt{\pi}} \times log_2\left(1 + exp\left[\frac{\sqrt{8}\sigma_P x_n + 2\mu_P + \varsigma\, ln\left(a_j\right)}{\varsigma}\right]\right)\right\}\end{aligned} \tag{12}$$

(b) RD Link: the average spectral efficiency of RD link is

$$\xi_d = \frac{(1-\tau)}{2}\sum\nolimits_{j=0}^{1}p_j\int_0^{\infty} log_2(1+\gamma)f_{\gamma_{d,j}}(\gamma)d\gamma \tag{13}$$

We need to analyze the PDF of SNR at the node D. It is known that Gamma distribution is similar to the specific LogN, the SNR of the PLC follows the LogN distribution, and the sum of the LogN variables still follows the LogN. Therefore, we will approximate the $\left(h_2^w\right)^2$ to LogN using Moment Generating Function (MGF) approximation algorithm, which makes it converte into the performance analysis problem under the same distribution of LogN-LogN.

Known $\left(h_2^W\right)^2$ meets the Gamma distribution, its MGF is $M_W(s) = (1 + \Omega/m)^{-m}$. First of all, we approximate $\left(h_2^W\right)^2$ to LogN, namely $(h_2^W)^2 \sim Log\, N(\mu_W, \sigma_W^2)$. By using

Hermite–Gauss quadrature method, we can get the MGF of the LogN variable, $M_{LN}(s) = \sum_{n=1}^{N} \omega_n \cdot exp\left(-s \cdot exp\left(\sqrt{2}\sigma_W a_n - \mu_W\right)\right)/\sqrt{\pi}$.

By the simultaneous MGF above, we can get

$$(1+\Omega/m)^{-m} = \sum\nolimits_{n=1}^{N} \frac{\omega_n}{\sqrt{\pi}} exp\left(-s \cdot exp\left(\sqrt{2}\sigma_W a_n - \mu_W\right)\right) \tag{14}$$

Choose two fixed s values, we can obtaine the equations about μ_W and σ_W^2, then we can get $\gamma_{d,W} \sim Log\,N\left(\mu_A, \sigma_A^2\right)$, where $\mu_A = \mu_W + ln((1-\rho)P_r/N_W)$,$\sigma_A^2 = \sigma_W^2$.

Knowing $\gamma_{d,P} \sim Log\,N\left(\mu_B, \sigma_B^2\right)$, where $\mu_B = \mu_P + ln(\rho P_r/N_{Pl})$, $\sigma_B^2 = 4\sigma_P^2$, the sum of the LogN variables follows the LogN $\gamma_d = \left[\gamma_{d,W} + \gamma_{d,P}\right] \sim LogN\left(\mu_D, \sigma_D^2\right)$. Denote the MGF respectively of $\gamma_{d,W}$, $\gamma_{d,P}$ and γ_d as $M_{d,W}(s)$, $M_{d,P}(s)$ and $M_d(s)$. Because the MGF of the sum of the two variables is equal to the product of the two MGF, the MGF of the γ_d is equal to $M_d(s) = M_{d,W}(s) \times M_{d,P}(s)$. Choosing fixed values of s, we can get the distribution of the SNR at D as $\gamma_d = LogN\left(\mu_D, \sigma_D^2\right)$.

Considering that the noise of power line is impulse noise, the SNR of destination node under fixed probability can be obtained:

$$f_{\gamma_{d,j}}(\gamma) = \frac{1}{\gamma\sigma_{D,j}\sqrt{2\pi}} exp\left[-\frac{\left(ln\gamma - \mu_{D,j}\right)^2}{2\sigma_{D,j}^2}\right], j \in \{0,1\} \tag{15}$$

Therefore, the spectral efficiency of the RD link can be written as

$$\xi_d = \frac{(1-\tau)}{2} \sum\nolimits_{j=0}^{1} \int_{-\infty}^{\infty} \frac{p_j}{\sqrt{\pi}} h(x) exp\left[-x^2\right] dx \tag{16}$$

where $h(x) = log_2\left[1 + exp\left(\sqrt{2\sigma_{D,j}^2}x + \mu_{D,j}\right)\right]$. The EE derivation of the relay-destination link can be obtained:

$$\eta_d = \frac{(1-\tau)}{2\left(P_{dyn} + 3P_{stc} + P_{idl}\right)} \times \sum\nolimits_{j=0}^{1} \sum\nolimits_{n=1}^{N} \left\{\frac{p_j w_n}{\sqrt{\pi}} \times log_2\left(1 + exp\left[\sqrt{2\sigma_{D,j}^2}x + \mu_{D,j}\right]\right)\right\} \tag{17}$$

Finally, choosing the minimum of η_r and η_d, we can yield the overall EE of the proposed P/W-DF-EH system. The EE of DF-EH system is shown in literature [11].

3.2 System Outage Probability

When the system information rate R is less than the required minimum rate threshold R_{th}, the normal communication of the system will be interrupted. Let the threshold be R_{th} and $\gamma = \exp(2R_{th}) - 1$. Then the outage probability of the system is as follows:

$$P_{out} = P_r(I < R_{th}) = 1 - [1 - P_r(\gamma_r < \gamma)] \times [1 - P_r(\gamma_d < \gamma)] \tag{18}$$

Substituting the cumulative distribution function (CDF) of γ_r and γ_d into the above equation, we can obtain the outage probability:

$$P_{out} = 1 - \left[1 - \sum\nolimits_{j=0}^{1} p_j Q\left(\frac{ln\gamma - \mu_{Rj}}{\sigma_{Rj}^2}\right)\right] \times \left[1 - \sum\nolimits_{j=0}^{1} p_j Q\left(\frac{ln\gamma - \mu_{Dj}}{\delta_{Dj}^2}\right)\right] \tag{19}$$

where $\mu_{R0} = 2\mu_P + ln(P_s/N_G)$, $\mu_{R1} = 2\mu_P + ln(P_s/(N_G + N_I))$, $\sigma_{R0}^2 = \sigma_{R1}^2 = 4\sigma_P^2$, the outage probability of the DF-EH system can be straightforwardly obtained from (19) by making the following substitutions: $\mu_{D0} = 2\mu_P + ln(P_r/N_G)$, $\mu_{D1} = 2\mu_P + ln(P_r/(N_G + N_I))$.

4 Numerical Results and Discussions

In this section, we carried out Monte Carlo simulation experiment, which compared with the theoretical results, and analyzed the influence of system parameters on the EE and average outage probability of the two systems. Unless clearly stated otherwise, we will be using: $P_s = P_{re} = 1\ W$, $P_{stc} = 0.9\ W$, $P_{idl} = 0.1\ W$, $\sigma_P^2 = 4dB$, $m = 3.5$, $\kappa = 1$, $\rho = 0.5$, $K = N_I/N_G = 3 \times 10^3$. Let S_{SNR} represents the average SNR of the channel, so $N_W = N_{Pl} = 1/S_{SNR}$.

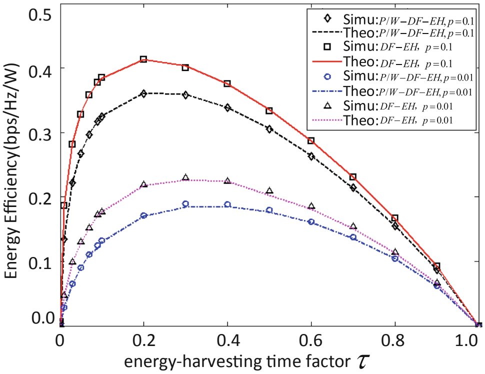

Fig. 2. EE of P/W-DF-EH and DF-EH system versus the energy-harvesting time factor.

We first analyzed the influence of energy-harvesting time factor τ and impulse noise probability on the energy efficiency performance of the two systems, where $P_{re} = 0$, then the relay forwards signal completely depends on the harvested energy. From the analysis of Fig. 2, the following conclusions can be drawn: (1) The theoretical performance of the system is basically consistent with the simulation results, which verifies the accuracy of the theoretical analysis. (2) For a given τ, higher noise pulse probability leads to better energy efficiency performance. That is because increasing the noise probability implies more energy can be harvested. (3) In these two systems, we can observe that the system becomes energy inefficient when τ is either too small or too large, so there exists an optimal energy-harvesting time that maximizes the system performance in the different values of p. This is basically because when τ is too small, there is not enough time to collect energy, when τ is too large, unnecessary energy is harvested at the cost of less information transmission time, which both reduce EE. (4) The EE of P/W-DF-EH system is lower than that of DF-EH system, which is because adding the wireless parallel communication will increase the power consumption of the system.

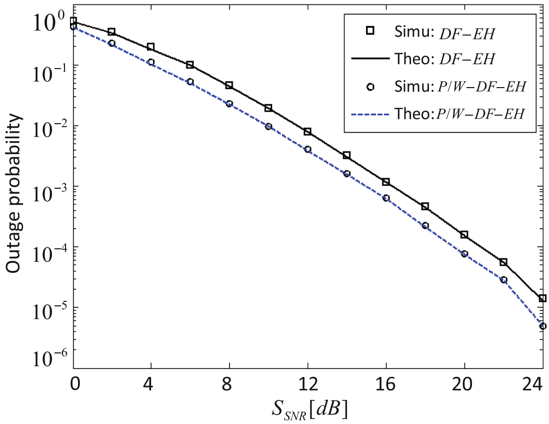

Fig. 3. The average outage probability of P/W-DF-EH and DF-EH system versus S_{SNR}

Through the analysis of Fig. 2, we know that there is an optimal energy-harvesting time factor in each system. Optimal energy harvesting time τ^* can be obtained according to $\partial\eta(\tau)/\partial\tau = 0$. Figure 3 shows the relationship between the two system outage probabilities and the average SNR of the channel based on the optimal energy-harvesting time factor. System parameters are set as follows: $p = 0.1$, $K = 10$. As can be seen from the results, with the increase of the S_{SNR}, P/W-DF-EH system has a lower average outage probability than the DF-EH system. The reliability of the system can be improved by adding wireless parallel channels. We can select the appropriate time factor and power split ting coefficient in the P/W-DF-EH system, so that the effectiveness and reliability of the system can be optimized at the same time.

5 Conclusions

This paper studies the performance of the dual-hop PLC/wireless parallel communication system. In order to improve the energy efficiency of the system, we proposed energy-harvesting at the relay, adopting the time-switching relaying protocol. The results show that the EE of the proposed system is lower than that of the DF-EH system due to the increase of power consumption, but the outage performance is better than that of the DF-EH because of adding the wireless channel. The optimization of energy-harvesting time is the key to achieve the highest energy efficiency.

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