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Overall outage event of self-sustaining low-power cooperative relaying networks

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ABSTRACT

This paper investigates the implementation of the household low-power energy harvesting (LoPEH) wireless sensor networks (WSN) over log-normal fading channels. The relays are battery-operated and the stochastic harvested energy flow to the batteries is characterized with the Markov property of energy buffer status. The communication is established with the combination of direct link and cooperative relays. The best relay is chosen based on a relay selection (RS) scheme namely optimal relay selection (OPRS). It can be drawn that within a particular range of signal-to-noise ratio (SNR), the energy harvesting (EH) relay-aided protocol can remarkably boost the overall system performance. On the other hand, the study reports how increasing the log-normal channel variance can degenerate the in-studied EH relaying protocol.

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1. INTRODUCTION

Simultaneous wireless information and power transfer (SWIPT) networks are classified into two categories: direct and cooperative relaying system. The relays are employed with several protocols which help to guard them against extreme signal fading, i.e., amplify-and-forward (AF), and decode-and-forward (DF). Moreover, these relaying networks operate in full-duplex (FD), half-duplex (HD) or even hybrid FD/HD mode, allowing the system to switch opportunistically between the two modes, which outperforms both the standalone modes, [1]-[3]. To further improve the network performance, theories about opinion dynamics [4] and block chain for security issues [5] could be promising drivers.

Besides, network designers have to consider as well the fading modelling techniques for the wirelesschannel to find the best fit for the simultaneous wireless information and power transfer (SWIPT) systems in practice [6]. Log-normal fading channel, indeed, showsit strength in characterizing indoor shadowing effect of human body movements, as well as obstacle mobilitiesand walls of buildings [7]-[12]. Thus, it is an appropriate model for modelling shadow effect for internet of things (IoTs) and smart city applications despite its drawback in modelling the small-scale fading in low-power sensor network. In the context of the aforementioned indoor scenarios, the utilization of cooperativerelaying system becomes inevitably a necessity. It is beneficial not only for increasing the channel capacity but also for spreading the network coverage range while opposing the shadowing effect [13]. Nevertheless,the higher number of relays means the higher level of inter-relay interference problem, which requires relay selection (RS) schemes to solve [14]-[16]. Moreover, it is obvious that battery plays an essential role in improving the system performance of cooperative battery-operated relaying networks. In such network scenarios, in [17]-[20]

investigated the dynamic behaviours of finite-capacity battery model and its topology utilizing the property of the Markov model. In particular, the batteries at the relays have some initial energy and will harvest additional energy during the transmission process. Additionally, the battery status is considered when choosing the best relay.

All the aforementioned technologies, although being applied solely for wireless networks, can be combined with household low-power energy harvesting (LoPEH) wireless sensor networks (WSN) to bring about their advantages for smart homes and smart cities development. A limited number of studies have proved that utilization of relays can effectively eliminate the LoPEH WSN's problems of high noise and signal attenuation [21]-[23]. This opens up a bright future for 5G development especially for indoor applications, multi-building LoPEH WSN, whereas there are underground constructions, metal and concrete walls [24]-[25].

With inspiration taken from the above works, this paper conducts the performance analysis of relaying SWIPT systems in terms of the overall outage event (OE) with a relay selection (RS) scheme so-called optimal relay selection (OPRS) for multi-relay cooperative wireless networks in FD-AF protocol. The LoPEH WSN uses battery-operated relays and the shadowing effects were simulated with log-normal fading. Thanks to the Markov property of the energy buffer status, the stochastic property of the harvested energy flow can be characterized with a proposed active-passive model. The rest of this paper is arranged as follows: i) section 2 presents the system model, ii) section 3 analytically derives the performance indicator of the proposed the Markov battery model, and iii) section 4 subsequently presents the numerical results. Finally, this paper is summarized in conclusions.

2. SYSTEM MODEL

A cluster network is illustrated in Figure 1 which includes a source (S), a destination (D), and a cluster (C) of in-between K cooperative relays (R_i) $(1 \leq i \leq N = K)$ installed in a LoPEH WSN. The assumed system is under coverage extension scenarios, whereas the (S) and (D) nodes are considerably distant from each other, which makes the direct link between them so attenuated that the communication cannot be realized without relays [26]. Besides, cooperative relaying networks can be utilized as well for situations where the surrounding environment causes deep shadowing effects on the direct link with physical obstacles' mobility [27]. Furthermore, it is assumed that the carrier and symbol synchronization are ideal, and each terminal knows the channel state information (CSI) in advance. Information flows from (S) node to (D) node given that (S) is powered by a conventional stable source being P_s and (R) node is powered by a battery P_R implemented with the energy harvesting (EH) module. In addition, there is an additive white Gaussian noise (AWGN), $n_j, j \in \{r, d\}$ with zero mean and variance N_0 respectively at $i - th$ (R) and (D) nodes.

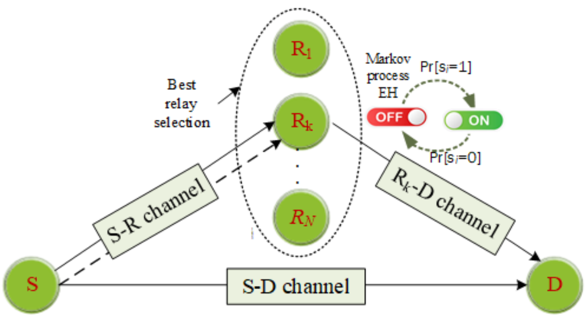

Figure 1. System models

Besides, Figure 1 schematically presents the distances between $(S) - (R)$, $(R) - (D)$, and $(S) - (D)$ nodes which are denoted by $d_{s,r}$, $d_{r,d}$, and $d_{s,d}$ with corresponding channel coefficients $l_{s,r}$, $l_{r,d}$, and $l_{s,d}$. Similar to the configurations for studying the log-normal fading channels in [28], the (S) and (D) nodes are each equipped with an antenna. Every (R) node is implemented with AF protocol and equipped with two antennas (one for receiving and the other for transmitting purpose). As aforementioned, this FD operation inevitably introduces the loop interference channel to the system indicated by $l_{r,r}$. Particularly, the communication time is split into slots given that within each time slot, the $i - th$ relay R_i , $(R_i \in N)$ is selected according to some relay selection (RS) scheme to aid the (S) node's transmission. In a signal block, $s(t)$ denotes the narrow-band transmit signal at (S), (R) has zero mean, and $E[|s(t)|^2] = 1$ with E denoting the statistical mean operation.

Moreover, there are assumed independent and identically distributed log-normal random variables (RVs) $l_{s,r}^2$, $l_{r,d}^2$ and $l_{s,d}^2$, respectively assigned with parameters $\mathcal{LN}\left(2\omega_{l_{s,r}}, 4\Omega_{l_{s,r}}^2\right)$, $\mathcal{LN}\left(2\omega_{l_{r,d}}, 4\Omega_{l_{r,d}}^2\right)$, and $\mathcal{LN}\left(2\omega_{l_{s,d}}, 4\Omega_{l_{s,d}}^2\right)$. The loop interference channel $l_{r,r}^2$ under log-normal distribution is assigned with parameter $\mathcal{LN}\left(2\omega_{l_{r,r}}, 4\Omega_{l_{r,r}}^2\right)$. This parameter plays an essential role in characterizing the loop interference strength, and thus, determines the overall performance of the FD relaying network.

Remarkably, $(S)-(R)$ and $(R)-(D)$ links are under the influence of quasi-static block fading. This means that the channels are constant at time block T, then vary from block to block as they are independently and identically distributed (i.i.d.) in log-normal fashion. The probability density function (PDF) and the cumulative distribution function (CDF) of the RV X in log-normal distribution are respectively calculated by:

$$F_X(z) = 1 - Q\left(\frac{\frac{10}{\ln(10)}\ln(z) - 2\omega_X}{2\Omega_X}\right) \text{ and } f_X(z) = \frac{10/\ln(10)}{z\sqrt{8\pi\Omega_X^2}} e^{\left(-\frac{\left(\frac{10}{\ln(10)}\ln(z)-2\omega_X\right)^2}{8\Omega_X^2}\right)}$$

Inwhich $\xi = \frac{10}{\ln(10)}$ is a scaling constant and $Q(\cdot)$ is the Gaussian Q-function, $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{\left(-\frac{t^2}{2}\right)} dt$

2.1. Direct link without cooperative protocol

As aforementioned, the outage event (OE) is an indicator of the system performance. This is the probability that the instantaneous capacity falls below a given threshold bits per channel use (BPCU) being R_0, and $Pr\left[C_{s,d} < R_0\right]$. Hence, by utilizing the CDF of the log-normally distributed RV $\left|l_{s,d}\right|^2$, the OE of the direct link can be expressed as:

$$OE_{s,d} = \Pr\left(\left|l_{s,d}\right|^2 < \left(2^{\frac{R_0}{W}} - 1\right)\frac{N_0 d_{s,d}^m}{P_s}\right) = 1 - Q\left(\frac{\xi\ln(a) - 2\omega_{s,d}}{2\Omega_{s,d}}\right) \quad (1)$$

Where $a = \frac{\gamma_0 N_0}{P_s d_{s,d}^{-m}}$, and $\gamma_0 = 2^{R_0/W} - 1$, m is the path loss exponent, R_0 is the data transmission rate, W is the frequency bandwidth.

2.2. Relay-aided cooperative protocol

Definition 1. The relay-aided cooperative protocol is utilized to further improve the ergodic capacity, hence the LoPEH WSN performance. If the direct link is considerably attenuated with deep fading, an alternative relay link will be selected among Ks to conduct the transmission instead, on condition that it possesses enough energy for the task.

Accordingly, the time frame T for completing one transmission cycle from (S) to (D) is split into three slots according to the time-switching relaying (TSR) protocol as depicted in [16]. The first time slot being τT (τ is EH time factor, $0 \le \tau \le 1$) is dedicated to EH purpose whereas (R_i) can harvest the energy from the signal broadcasted from the (S) node. The rest is halved with $(1-\tau)T/2$ utilized for $(S)-(R_i)$ and $(R_i)-(D)$ information transmission.

Within the first time slot, based on the energy harvested at the i_{th} (R) node, $E_H = \frac{\eta\tau T P_s\left|l_{s,r_i}\right|^2}{d_{s,r_i}^m}$, the relay's transmit power can be formulated as:

$$P_{R_i} = \frac{E_H}{(1-\tau)T} = \frac{\eta\tau P_s\left|l_{s,r_i}\right|^2}{(1-\tau)d_{s,r_i}^m} \quad (2)$$

Where $0 \le \eta \le 1$ is the EH efficiency specified mainly by the characteristics of the circuitry.

For the second time slot being the information transmission phase, the received signal at the i_{th} (R) can be calculated by:

$$y_r(t) = \sqrt{\frac{P_s}{d_{s,r_i}^m}}\, l_{s,r_i} s(t) + l_{r,r} r(t) + n_r \quad (3)$$

Where the information signal $s(t)$ is normalized as $E\left[|s(t)|^2\right] = 1$, and the loop interference $r(t)$ of the FD relays satisfies $E\left[|r(t)|^2\right] = P_{R_i}$.

It is noteworthy that a relay in a FD multi-relay cooperative system can distinguish its signal with others' [29]. Therefore, it can apply interference cancellation for its own loop interference reduction. The post-cancellation signal at the relay, (3) can be expressed as:

$$y_r(t) = \sqrt{\frac{P_S}{d_{s,r_i}^m}} l_{s,r_i} s(t) + \widehat{l_{r,r}} \hat{r}(t) + n_r \tag{4}$$

Whereas $\widehat{l_{r,r}}$ is the residual loop interference remaining after imperfect interference cancellation process, and $E\{|\hat{r}(t)|^2\} = P_{R_i}$.

In FD-AF system, after base-band processing at (R_i) following (4), the signal is amplified and forwarded to (D). Accordingly, the (D) node receives the signal given by (5):

$$y_d(t) = \sqrt{\frac{P_S P_{R_i}}{d_{s,r_i}^m d_{r_i,d}^m}} l_{s,r_i} l_{r_i,d} G s(t) + \sqrt{\frac{P_{R_i}}{d_{r_i,d}^m}} l_{r_i,d} l_{r,r} G r(t) + \sqrt{\frac{P_{R_i}}{d_{r_i,d}^m}} l_{r_i,d} G n_r + n_d \tag{5}$$

Where the relay gain G normalizes the instantaneous received power while permitting the relay transmission with maximum power as:

$$P_s \to \infty, G = \frac{1}{\sqrt{\frac{P_S}{d_{s,r_i}^m}\left|l_{s,r_i}\right|^2 + \left|\widehat{l_{s,r_i}}\right|^2 P_{R_i} + N_0}} \approx \frac{1}{\sqrt{\frac{P_S}{d_{s,r_i}^m}\left|l_{s,r_i}\right|^2 + \left|\widehat{l_{s,r_i}}\right|^2 P_{R_i}}}$$

For such case, after substituting G into (4) some basic algebraic manipulations are performed to obtain the end-to-end signal-to-noise ratio (SNR) of the i_{th} relay at (D), as in [2].

$$\gamma_{s,R_i,d} = \frac{\frac{P_S \gamma_{S,R_i}}{P_{R_i}\gamma_{R,R_i}} P_{R_i}\gamma_{R_i,D}}{\frac{P_S \gamma_{S,R_i}}{P_{R_i}\gamma_{R,R_i}} + P_{R_i}\gamma_{R_i,D} + 1} \tag{6}$$

Where:

$$\gamma_{S,R_i} = \left|l_{s,r_i}\right|^2 d_{s,r_i}^{-m},\ \gamma_{R_i,D} = \left|l_{r_i,d}\right|^2 d_{r_i,d}^{-m} \text{ and } \gamma_{R,R_i} = \left|l_{r,r}\right|^2$$

Accordingly, it should be noted that the instantaneous capacity of the FD-AF-TSR system is obtainable from:

$$C_{s,R_i,d} = (1-\tau)\log_2\left(1+\gamma_{s,R_i,d}\right) \tag{7}$$

Here, RS schemes for the relay-aided cooperative LoPEH wireless sensor networks, namely optimal relay selection (OPRS) is established with regard to (6). Thus, the best relay k_{th} is activated when $k = arg\,\max_i\{\gamma_{s,R_i,d}\}$. The best selected relay is responsible for establishing the communication and subjects to the performance analysis.

3. PERFORMANCE ANALYSIS

3.1. Energy storage modeling at relay

Thanks to the stationary stochastic process stated in [30], ones can denote the minimum energy required for R_k activation and the energy which is harvested from the environment during the period of the k_{th} signal block as en_k. Particularly, the very first focus is paid on R_k without energy storage working solely on en_k. The relay runs out of energy if $en_k \le P_{R_k}$. The probability of such events is so-called energy-exhausted probability and expressed as follows:

$$OE_{\Bbbk} = Pr\left[en_k < P_{R_k}\right] = \int_0^{P_{R_k}} f_{en_k}(x)dx \tag{8}$$

Where $f_{en_k}(x)$ signifies the PDF of the stationary stochastic process being en_k.

On the other hand, for most of the applications in practice, the R_k is installed with a battery whose capacity is assumed to be en_{max}. The energy consumption for the k_{th} signal block transmission is denoted as $OE_{\Bbbk}$. With regard to the relay-aided cooperative protocol scenario described in Definition 1 , ones can express the $OE_{\Bbbk}$ with the stationary random function as follows.

$$Pr(ou_k) = \begin{cases} OE_{s,d}/\mathcal{K} & if\ Pr\left(ou_k = P_{R_k}\right) \\ 1 - OE_{s,d}/\mathcal{K}, & if\ Pr(ou_k = 0) \\ 0 & otherwise \end{cases} \quad (9)$$

Where factor $\mathcal{K}$ indicates that every (R) node is activated with an equal probability.

It is noted that en_k and ou_k are two stationary and independent variables. To describe the energy buffer status following the Markov stochastic process, s_k is utilized, and it indicates as well the initial energy amount stored at (R_k) when the k_{th} signal block transmission starts. Accordingly, the stationary PDF of s_k being $f_{s_k}(x)$ is obtained as a combination of (8), (9) and the original PDF of en_k. Theory-wise, $f_{s_k}(x)$ is sufficient for describing all the stochastic characteristics of the EH module. Nonetheless, this discretized model has a large number of possible energy buffer statuses. Therefore, a simplified model is proposed to limit the number of statuses to two processing steps in the Lemma 1.

– Lemma 1. To decide whether the direct link or the alternative relaying link is going to be utilized for data transmission, $\mathrm{s_k}$ is compared with the possible energy consumption at (R_k) as: i) If $s_k \geq P_{R_k}$, the $\mathrm{k_{th}}$ relay is activated and relay the signal for (S)-(D) link on condition that the direct $(S)-(D)$ link is too weak to perform its task and ii) If $s_k \leq P_{R_k}$, the $\mathrm{k_{th}}$ relay remains inactivated and consumes no energy. Communication is realized via direct link.

Practically, these two statuses can be utilized for characterising the flow of harvested energy. This is named 1-0 (on/off) model with denotation s_k', please refer to Figure 1. Thanks to the stationary PDF of s_k denoted as $f_{s_k}(x)$, the stationary PDF of s_k' can be derived as follows:

$$Pr(s_i') = \begin{cases} \int_{P_{R_k}}^{en_{max}} f_{s_k}(x)dx, & if\ Pr(s_i') = 1 \\ \int_0^{P_{R_k}} f_{s_k}(x)dx, & otherwise \end{cases} \quad (10)$$

To conclude, from the systematic point of view, a 1/0 (on/off status) model for the harvested energy flow is established and described in Theorem 1. For more details of how the original PDF of the harvested energy flow is derived and how the $f_{en_k}(x)$ is utilized for calculating $OE_{\mathcal{k}}$ with low computation complexity, please refer to [31]. It should be noted that this function is different from the original PDF being $f_{en_k}(x)$ of the harvested energy in (9).

3.2. Overall outage event

It is impossible to successfully establish the relay-aided link over the R_k all the time due to the effect of either deep fading or energy exhausting owing to the fluctuating renewable resources. Such an event is so-called overall OE, and is important for performance analysis. To formulate the OE event, we describe first the related premilinaries in Theorem 1:

– Theorem. 1 The relay-aided link in cooperative relaying LoPEH WSN is activated on condition that the direct link is insufficient for information transmission and the available energy stored at the relay node is greater than P_{R_k}. Furthermore, there is an EH module employed in R_k, which is characterized with parameters P_{R_k} and $OE_{\mathcal{k}}$. Thanks to this module, the stochastic property of the harvested energy can be captured with no loss. Given that at R_k, the available energy is sufficient for signal transmission, the overall OE of the FD-AF-TSR system in the proposed relay-aided cooperative LoPEH WSNs can be expressed as:

$$OE_{oc} = OE_{s,d} \times \prod_{k=1}^{K}\left[OE_{\mathcal{k}} + (1 - OE_{\mathcal{k}}) \times OE_{s,\mathcal{R}_{\mathcal{k}},d}\right] \quad (11)$$

By considering (7), the definition of the OE for $S - R_k - D$ link in case of the OPRS scheme, denoted as $OE_{s,\mathcal{R}_{\mathcal{k}},d}$, can be expressed in the below united manner.

$$OE_{s,\mathcal{R}_{\mathcal{k}},d} = Pr\left\{\frac{\frac{P_S\gamma_{S,R_k}}{P_{R_k}\gamma_{R,R_k}}P_{R_k}\gamma_{R_k,D}}{\frac{P_S\gamma_{S,R_k}}{P_{R_k}\gamma_{R,R_k}}+P_{R_k}\gamma_{R_k,D}+1} < \gamma_1\right\} \quad (12)$$

Where $\gamma_1 = 2^{R_0/(1-\tau)W} - 1$, and the selected R_k is different for the RS schemes. By utilizing the simple order statistic result obtained from (11) and (12), it is possible to express the overall OE of the proposed relay-aided cooperative transmission protocol under the OPRS scheme as follows.

$$OE_{\mathcal{oc}}(\gamma_1) = \left[1 - Q\left(\frac{\xi\ln(a) - 2\omega_{s,d}}{2\Omega_{s,d}}\right)\right] \times \left[OE_k + (1 - OE_k) \times OE_{\mathcal{s},\mathcal{R}_{\mathcal{k}},\mathcal{d}}(\gamma_1)\right]^K \tag{13}$$

Where:

$$OE_{\mathcal{s},\mathcal{R}_{\mathcal{k}},\mathcal{d}}(\gamma_1) = 1 - \frac{\xi}{\sqrt{8\pi\Omega_{l_{r,r}}^2}} \int_0^{\frac{1}{\phi\gamma_1}} \frac{1}{z} Q\left(\frac{\xi\ln(b) - 2(\omega_{l_{s,r}} + \omega_{l_{r,d}})}{\sqrt{2}(\Omega_{l_{s,r}} + \Omega_{l_{r,d}})}\right) e^{\left(-\frac{\left(\xi\ln(z) - 2\omega_{l_{r,r}}\right)^2}{8\Omega_{l_{r,r}}^2}\right)} dz,$$

$$b = \frac{N_0}{P_s} \frac{\gamma_1}{(1-\gamma_1\phi z)} \left(\frac{1}{\phi} + z\right), and\ \phi = \frac{\eta\tau}{(1-\tau)}$$

– Proof: here in this proof, the process to obtain the $OE_{\mathcal{oc}}$ expression in (11). According to (8) from which R_k is selected, it is possible to rewrite the OE of the FD-AF-TSR LoPEH WSNs in (12), under OPRS scheme as:

$$OE_{\mathcal{s},\mathcal{R}_{\mathcal{k}},\mathcal{d}} = Pr\left\{\frac{\frac{P_S\gamma_{S,R_k}}{P_{R_k}\gamma_{R,R_k}} P_{R_k}\gamma_{R_k,D}}{\frac{\gamma_{S,R_k}}{P_{R_k}\gamma_{R,R_k}} + P_{R_k}\gamma_{R_k,D} + 1} < \gamma_1\right\} \tag{14}$$

Noted that $\phi = \eta\tau/(1-\tau)$, $X = \gamma_{S,R_k}\gamma_{R_k,D}$, and $Y = \gamma_{R,R_k}$. By substituting (2) into (14) the OE of the FD-AF-TSR LoPEH WSNs can be rewritten as:

$$OE_{\mathcal{s},\mathcal{R}_{\mathcal{k}},\mathcal{d}} = Pr\left\{X < \frac{\gamma_1\left(\frac{1}{\phi} + Y\right)}{P_s - P_s\phi\gamma_1 Y}\right\} \tag{15}$$

Given that X is positive, the probability in (15) can be rewritten as

$$OE_{\mathcal{s},\mathcal{R}_i,\mathcal{d}} = \begin{cases} \Pr\left(X > \frac{\gamma_1\left(\frac{1}{\phi} + Y\right)}{P_s - P_s\phi\gamma_1 Y}\right) = 1, Y > \frac{1}{\phi\gamma_1} \\ \Pr\left(X \le \frac{\gamma_1\left(\frac{1}{\phi} + Y\right)}{P_s - P_s\phi\gamma_1 Y}\right), Y < \frac{1}{\phi\gamma_1} \end{cases} \tag{16}$$

Besides, the complementary CDF of X, as a product of two log-normally distributed RVs, is defined as:

$$\overline{F_X}(x) = Q\left(\frac{\xi\ln\left(\frac{\gamma_1\left(\frac{1}{\phi} + x\right)}{P_s - P_s\phi\gamma_1 x}\right) - 2(\omega_{l_{s,r}} + \omega_{l_{r,d}})}{\sqrt{2}(\Omega_{l_{s,r}} + \Omega_{l_{r,d}})}\right) \tag{17}$$

Using the PDF of log-normally distributed RV Y is obtained by:

$$f_Y(x) = \frac{\xi}{x\sqrt{8\pi\Omega_{l_{r,r}}^2}} \exp\left(-\frac{\left(\xi\ln(x) - 2\omega_{l_{r,r}}\right)^2}{8\Omega_{l_{r,r}}^2}\right) \tag{18}$$

Accordingly, the OE in (16) can be calculated as:

$$OE_{\mathcal{s},\mathcal{R}_i,\mathcal{d}} = 1 - \int_0^{\frac{1}{\phi\gamma_1}} f_Y(x)\overline{F_X}\left(\frac{\gamma_1\left(\frac{1}{\phi} + x\right)}{P_s - P_s\phi\gamma_1 x}\right) dx \tag{19}$$

Eventually, by substituting (17) and (18) into (19) in combination with (1). The (13) can be solved. This is end proof.

4. RESULTS AND DISCUSSION

This section presents the numerical results of Monte Carlo simulations of the overall OE of the relay-assisted cooperative wireless power-line communication network (PCLN) powered by a stable energy supplier, under the consider optimal relay selection scheme. The system parameters for the simulations are as follows. The energy-exhausted event at R_k, $OE_{k} = 10^{-1}$. Frequency bandwidth, $W = 2(W)$. Transmission rate threshold, $R_0 = 2$ (bps/Hz). Traditional stabilized power source, $P_s = 5$ (dB). Overall additive white Gaussian noises (AWGNs), $N_0 = 1$. EH efficiency, $\eta = 1$. EH time fraction, $\tau = 0.2$. Path-loss exponent, m $= 2$. Distance from $(S) - (R_k)$, $d_{s,r} = 5$ (m); $(R_k) - (D)$, $d_{r,d} = 5$ (m), and $(S) - (D)$, $d_{s,d} = 10$ (m) with corresponding channel mean $\Omega_{l_{s,r}} = \Omega_{l_{r,d}} = \Omega_{l_{s,d}} = 4$ (dB), and channel variance $\omega_{l_{s,r}} = \omega_{l_{r,d}} = \omega_{l_{s,d}} = 3\ (dB)$. The loop interference (R_k) channel mean $\Omega_{l_{r,r}} = 2$ (dB) and its corresponding channel variance $\omega_{l_{r,r}} = 3$ (dB). It should be noted that all the channel means and variances are log-normally distributed.

Figure 2 plots the overall OE of the cooperative relay-aided LoPEH WSNs versus the SNR. Three values of energy-exhausted probability OE_{k} of best RS being 0, 0.5 and 1 are illustrated. It should be emphasized that the curve corresponds to the traditional WSNs with direct link at $OE_{k} = 1$, and the relay-aided cooperative LoPEH WSNs with a constant power source at $OE_{k} = 0$. At $OE_{k} = 0.5$, the LoPEH can utilize both the direct link and the relay link (red, continuous curve) or only relay link (blue, continuous curve) for signal transmission. The overall OE curves decrease by an order of magnitude when OE_{k} increases from 0 to 1. It is obvious that the relay-aided LoPEH WSN curve at $OE_{k} = 0$ is the lowest within the consider SNR range, which indicates that it delivers the best system performance. In practice, a well-designed battery-operated system can have relatively small OE_{k}. Therefore, from theory and simulation results, it is reasonable to say that the installation of EH relays is significantly beneficial for the WSNs.

Furthermore, as SNR approaches 30 (dB), all the curves obtained from the OPRS scheme tend to converge to the lowest error floor providing zero diversity gain. The simulation results agree well with the theoretical analysis ensuring that the proposed scheme can be utilized further for comparison of system performance among other RS schemes to choose the most effective one. In addition, Figure 3 depicts the OE of the relay-aided cooperative LoPEH WSNs versus the SNR with different numbers of relay nodes, $K = 1, 3$ and 5, in the OPRS scheme. Besides, it should be noted that all cases are plotted with $OE_{k} = 10^{-1}$.

As aforementioned, the lower the curve, the better the system performance. It can be observed that as K increases from 1 to 5, the system performance improves correspondingly. It worth to mention that in practice, relays embedded with EH module are relatively affordable. Hence, raising the number of on-field relay nodes is considered effective not only in decreasing the overall OE but also in cost manner comparing to other methods. As aforementioned, because the trends of the simulation results agree well with the theoretical analysis, they can be utilized for comparison studies between different RS schemes to choose the most effective one for system performance.

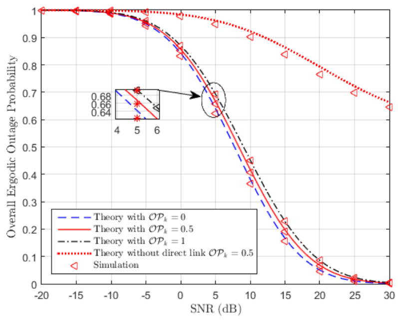

Figure 2. The overall OE versus SNR with different energy-exhausted probability

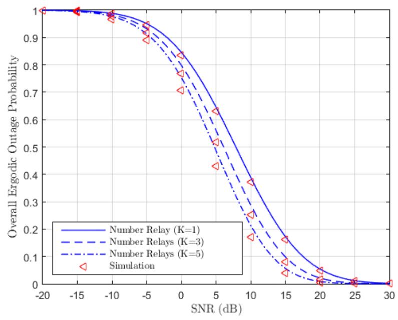

Figure 3. The overall OE versus SNR with the number of available relay nodes K

Figure 4 plots the overall OE behaviour under the influence of the EH parameter τ in the OPRS scheme. The theoretical analysis and simulation results are calculated with loop interference channel variance $\Omega_{l_{r,r}} = 2$ (dB) and 4 (dB), in combination with the fixed system parameter $P_s = 5$ (dB). The fact that the simulation results agree well with the analytical ones proves the correctness of the analysis. Additionally, it can be observed that as τ increases to 0.15 and 0.2 respectively for $\Omega_{l_{r,r}} = 2$ (dB) and 4 (dB), the OE sharply decreases. This results in a notable increase in system performance. Moreover, it is worth to emphasize that as τ value is equal to 0 or approaching 1, corresponding to the cases when the harvested energy amount gets too small or too large, the OE becomes extreme, because there is no resource that remains for data transmission. Besides, it should be noted that the system performance can be improved by unequal channel allocation following the relative channel distribution method.

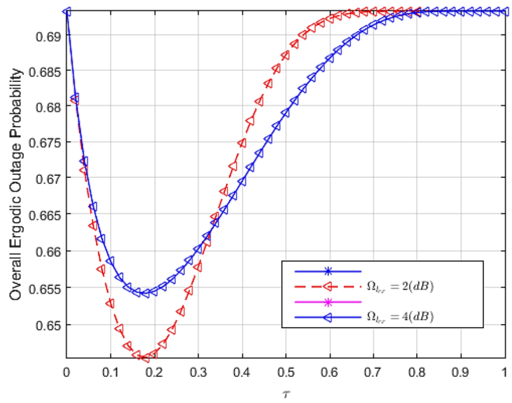

Figure 4. Compare the overall OE versus τ being the time switch

5. CONCLUSION

To summarize, the paper investigated the OE behaviour of a FD-AF RS scheme so-called OPRS, which provide zero diversity over log-normal fading channels in WSNs. Thanks to the characterized harvested energy flow, the two proposed cooperative relaying protocols can significantly reduce the OE leading to the considerable improvement of the LoPEH WSN performance. Additionally, the overall OE expression of the OPRS scheme was derived. Besides, as the overall OE plots versus the SNR and the EH time-switching in theory and in simulation results agree well with each other, the derived expressions can be utilized as references for comparison studies among other different RS schemes. Future papers will focus on analyzing the overall OE performance of EH relay-aided cooperative LoPEH WSNs under impact of different fading channel models along with their pros and cons. Besides, exploitation of multiple antennas and multiple relays distributed according to Poisson point process can be of interest to further optimized the existing LoPEH WSNs in every household for applications of smart homes and smart cities.

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