Role Selection for Energy Harvesting Cooperative Systems

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Abstract—This paper investigates the feasibility of deploying dynamic role selection (ROSE) mechanism in three-node energy-harvesting (EH) cooperative relay systems. A benchmark case of fixed role configuration is first studied which shows that full diversity order can be achieved and the system outage probability at high signal-to-noise ratio (SNR) is determined by the scaling laws of $\log c_0/c_0^2$ together with $\log(\log c_0)/c_0^2$, with $c_0$ denoting the transmit SNR at the source. Then, the ROSE mechanism is merged into the EH cooperative system and it is analytically shown that the ROSE mechanism can enhance the system diversity order to three, and the high-SNR outage behavior is no longer affected by the $\log c_0$ and $\log(\log c_0)$ factors. Interestingly different from the conventional EH relay system with fixed role configuration, in the high SNR regime our results show that the energy conversion efficiency and the power-splitting factor at the relay have negligible effect on the outage behavior of ROSE cooperation.

I. INTRODUCTION

Due to the wide application of wireless communications, our ambient environment is filled with various wireless transmissions, such as TV, radio, cellular, WiFi signals. On the other hand, the operation time of the mobile wireless devices are generally constrained by its limited power supply. Owing to the prevalence of wireless applications, Varshney showed new ways of prolonging the operation time for wireless devices and advocated that information and energy can be transported simultaneously [1]. Varshney’s seminal work has inspired a large amount of subsequent studies regarding simultaneous wireless information and power (energy) transfer, dubbed SWIPT. The early works focused on point-to-point communications. Assuming that the receiver can opportunely replenish energy from the wireless signal sent from the transmitter, [2] characterized the “outage-energy” and “rate-energy” tradeoffs. To address the practical constraints of designing SWIPT receivers, [3] presented two receiver architectures, i.e., the time-splitting (TS) and power-splitting (PS) based receivers, and studied the tradeoff between information rate and harvested energy. Under a multiple-input, multiple output (MIMO) broadcasting scenario, [4] studied the performance difference between the TS-based and PS-based receiver architectures.

The concept of SWIPT has also been extended to investigate the cooperative relay systems. For both TS-based and PS-based receiver architectures, [5] proposed two relaying protocols to enable energy harvesting (EH) and information processing at the relay, and determined the system throughput. In [6], a greedy switching policy where the relay node transmits when its residual energy ensures decoding at the destination was investigated. Chen et al. considered a wireless-powered cooperative system where the source and relay have no fixed energy supply and rely on the RF energy harvested from the access point (AP) for their cooperative information transmission [7]. Very recently, an EH dual-hop relaying system without/with co-channel interference (CCI) was investigated in [8], where the multi-antenna relay node is powered by either the information signal of the source or via both the source signal and CCI. From the above works, it can be observed that in EH relay systems, either the scheduling of relay nodes [7], or the operation mode of the wireless powered terminals [6] is quite different from that of conventional cooperative systems. This is partially due to the fact that the amount of harvested energy available to EH receiver depends largely on the instantaneous channel gains from the RF radiation source, which implies that exploiting the wireless fading fluctuation dynamically within RF powered systems may potentially boost the system performance. The work in [9] has shown that by designating the cooperative role of each node dynamically within cooperative relaying systems, a superior diversity gain can be achieved, which was referred to as role selection (ROSE) cooperation. However, unlike the conventional relay node with a fixed energy supply, when EH relaying is deployed within ROSE cooperative system, it is not clear whether the transmission reliability can still be enhanced, due to the random/fluctuating EH process. The main contributions of this paper are, at least, two-fold: (i) To counteract the fluctuating EH relaying process, we incorporate the ROSE mechanism into the considered system and analytically show that the ROSE mechanism can enhance the system diversity order to three, and the high signal-to-noise ratio (SNR) outage behavior is not affected by the $\log c_0$ and $\log(\log c_0)$ factors, and (ii) It is analytically shown that when ROSE mechanism is incorporated, the effects of the energy conversion efficiency and PS factor at the relay on the high-SNR outage performance become negligible, which is different from conventional EH relaying.

II. SYSTEM MODEL

We consider a three-node EH relaying system consisting of $N_1$, $N_2$, and $N_3$. Each node is equipped with a single antenna and operates in the half-duplex mode. As in [5],
[9], we consider a Rayleigh flat slow fading channel where the channel gains remain unchanged during each two-phase cooperative transmission process.

Based on the wireless fading environment, the cooperative role for each node, as a source, relay, or destination, can be dynamically designated for each two-phase cooperative transmission. After the cooperative role is appointed at each node, the one acting as a relay would start a “harvest and then cooperate” procedure1 [5], [11] to exploit wireless RF radiation energy from the source node, serving thus as an EH relay. As in [3], [5, Sect. IV] and [12], a PS-based receiver architecture2 is adopted where the power splitter at the relay splits the received signal in $\rho : 1 - \rho$ proportion. In addition, an amplify-and-forward (AF) operation is performed for its implementation simplicity.

A. Fixed Role Configuration with EH Relay

Without loss of generality, $N_i$ is assumed to be the source, $N_j$ the EH relay, and $N_k$ the destination. During the first phase of the information transmission process, the relay node collects the wireless energy and processes the received signal from the source node via the deployed power splitter, and during the second phase we assume that all the energy harvested during the first phase will be used up (best-effort transmission) to forward the source’s signal to the destination. Denoting each phase being a time frame of $T/2$, the harvested energy at $N_j$ during the first phase is given by $E_H = \eta \rho P_S g_{ij} T/2$, where $P_S$ denotes the transmit power of the source node $N_i$, $\rho$ and $\eta$ are, respectively, the PS factor and the energy conversion efficiency at the relay $N_j$, both belonging to $[0, 1]$, and $g_{ij}$ represents the channel power gain of the link $N_i \rightarrow N_j$. With this harvested energy, the transmit power at the relay $N_j$ of the second phase becomes $P_R = E_H T/2 = \eta \rho P_S g_{ij}$. Consequently, the end-to-end SNR of the dual-hop AF relaying link $N_i \rightarrow N_j \rightarrow N_k$ can be formulated as

$$\gamma_{ij} = \frac{\eta \left( \frac{P_s}{N_0} \right)^2 g_{ij}^2 g_{jk}^2 (1 - \rho) + \frac{\eta \rho}{N_0} g_{ij} (1 - \rho) + 1}{\eta \left( \frac{P_s}{N_0} \right)^2 g_{ij}^2 g_{jk}^2 (1 - \rho)} \approx \frac{\eta \left( \frac{P_s}{N_0} \right)^2 g_{ij}^2 g_{jk}^2 (1 - \rho) + \frac{\eta \rho}{N_0} g_{ij} (1 - \rho) + 1}{\eta \left( \frac{P_s}{N_0} \right)^2 g_{ij}^2 g_{jk}^2 (1 - \rho)} = \frac{\tilde{P}_S \left( 1 - \rho \right) \eta \tilde{g}_{ij} \tilde{g}_{jk}}{\eta \tilde{g}_{ij} + 1},$$

(1)

1Since the relay node acts as a “helper” to forward the source’s information to the destination, it is reasonable to assume that the relay is reluctant to consume its own fixed energy supply (e.g., battery power) [10]. In contrast, the source node is assumed to consume its own (fixed) energy supply to convey its own information.

2For ROSE cooperation, since each node may serve as a relay node during one cooperation process, each one of the three nodes will be equipped with a PS-based EH receiver and works as an EH relay when it is designated as a relay node.

3Herein, similar to [13], [14], we omit the independent noise variance in the denominator to make the analysis tractable. As shown in [13], [14] and in the numerical results of this work, such a setting will make the subsequent analysis tractable and asymptotically approaches to the original case at high SNR.

where $N_0$ denotes the variance of the overall additive white Gaussian noise (AWGN) at each receiving node, $\tilde{P}_S \triangleq (1 - \rho)P_S$, $\tilde{\eta} \triangleq \eta \rho$, $\tilde{g}_{ij} \triangleq \tilde{g}_{ij}$, and $\tilde{g}_{jk} \triangleq \tilde{g}_{jk}$. Under Rayleigh fading conditions, $g_{ij}$ conforms to an exponential distribution with mean $\sigma_{ij}$. Accordingly, $\tilde{g}_{ij}$ and $\tilde{g}_{jk}$ conform to exponential distributions with means $\tilde{\sigma}_{ij} \triangleq \sigma_{ij}/(1 - \rho)$ and $\tilde{\sigma}_{jk} \triangleq \sigma_{jk}/(1 - \rho)$, respectively. We denote the statistical average of $g_{ij}$, $\gamma_{ij}$, $\tilde{\gamma}_{ij}$, $\tilde{\gamma}_{jk}$, and $\tilde{\gamma}_{jk}$ being the distance between $N_i$ and $N_j$, and $m$ being the path loss exponent. At the destination $N_k$, signals from the direct and relaying links are processed using maximal-ratio combining (MRC) and the received SNR is given by

$$\tilde{\gamma}_{jk} \approx \frac{\tilde{P}_S}{N_0} \tilde{g}_{jk} + \frac{\tilde{P}_S (1 - \rho) \tilde{\eta} \tilde{g}_{ij} \tilde{g}_{jk}}{\tilde{\eta} \tilde{g}_{jk} + 1},$$

(2)

where $\tilde{g}_{ik} \triangleq \tilde{g}_{ik} \eta \tilde{g}_{jk}$ is subject to an exponential distribution with mean $\tilde{\sigma}_{ik} \triangleq \sigma_{ik}/(1 - \rho)$. In order to facilitate the following theoretical analysis, we adopt the well-known harmonic mean-minimum inequality to develop the following upper bound [14]

$$\tilde{\gamma}_{jk} \leq \frac{\tilde{P}_S}{N_0} (\tilde{g}_{ik} + (1 - \rho) \tilde{g}_{ij} \min[\tilde{\theta}_{ij}], 1) \leq \tilde{\gamma}_{jk}$$.  

(3)

Without loss of generality, we set $i = 1$, $j = 2$, and $k = 3$ for the fixed role configuration, and define $\tilde{\gamma}_{ij}^{\text{FixRole}} \triangleq \tilde{\gamma}_{ij}^{\text{ROSE}}$, $\tilde{\gamma}_{jk}^{\text{FixRole}} \triangleq \tilde{\gamma}_{jk}^{\text{ROSE}}$.

B. Dynamic Role Configuration with EH Relay

Similar to [9], the role decision can be carried out by any one of the three nodes $N_1$, $N_2$, and $N_3$. The role decision result is then broadcasted by the role decision node such that each node is informed of its cooperative role in the subsequent information transmission process. Once the cooperative role is defined for each node, the two-phase cooperative transmission is initiated, which is the same as the counterpart of the fixed role configuration. Based on (2), the received SNR of the best role configuration after the MRC processing at the destination can be written as

$$\tilde{\gamma}_{ij}^{\text{ROSE}} = \max_{i, j, k \in \{1, 2, 3\}} \left[ \tilde{\gamma}_{ij}^{\text{ROSE}} \right] \leq \max_{i, j, k \in \{1, 2, 3\}} \left[ \tilde{\gamma}_{ij}^{\text{ROSE}} \right] \leq \tilde{\gamma}_{ij}^{\text{ROSE}}.$$

(4)

Notably, to make this centralized role decision, the role decision node has to collect the global channel state information (CSI) and then makes role decision based on (4).

III. ASYMPTOTIC OUTAGE PROBABILITY OF THE FIXED ROLE CONFIGURATION

For a given end-to-end spectral efficiency threshold $R_0$ bit/s/Hz, the system outage probability of the fixed role configuration can be written as

$$P_{\text{out}}^{\text{FixRole}} = \Pr \left[ \frac{1}{2} \log_2 \left( 1 + \tilde{\gamma}_{ij}^{\text{ROSE}} \right) < R_0 \right] = \Pr \left( \tilde{\gamma}_{ij}^{\text{ROSE}} < 2^{2R_0 - 1} \triangleq \tau \right),$$

(5)

As in [5, Eqs. (3) and (5)], the overall AWGN denotes the combination of antenna and conversion AWGN at each receiving node.
To proceed, we employ the upper bound of the end-to-end SNR to achieve the outage lower bound, given in (6) and shown at the top of this page, in which \( c_0 \triangleq \frac{P_S}{N_0} \). By employing the total probability theorem [15], \( J_1 \) can be re-expressed as

\[
J_1 = \left(1 - e^{-\frac{\tau}{\sigma_1^2}}\right) - \frac{1}{\sigma_1^2} \int_0^{\tau'} e^{-\frac{\tau'}{\sigma_1^2}} dy
\]

in which Step (a) holds owing to the Taylor series expansion of the exponential function. On the other hand, by formulating \( J_2 \) as an one-fold integral and applying the differential calculus rule [16, Eq. (0.410)], we can arrive at an asymptotic expression for \( J_2 \) with the aid of [17, Eqs. (5.1.1) and (5.1.11)] as

\[
J_2 \simeq \frac{(\tau')^2}{2\sigma_2^2\sigma_1^2} \left(1 - e^{-\frac{\tau'}{\sigma_2^2}}\right)
\]

\[
-\frac{2\eta\sigma_2^2\sigma_2^2}{(\tau')^2} \left(C_{\text{Euler}} + \ln\left(\frac{\tau' - k_0\tau'\ln\tau'}{\sigma_1^2}\right)\right)
\]

\[
-\frac{(\tau')^2}{2\sigma_0^2\sigma_1^2\sigma_2^2} \left(1 - e^{-\frac{\tau'}{\sigma_2^2}} - \frac{1}{2\sigma_2^2}\right), \tag{8}
\]

where \( C_{\text{Euler}} = 0.5772156649 \) is the Euler-Mascheroni constant and \( k_0 = 10/\ln(100(1 - \rho)/\tau) \). Summarizing the foregoing results, we establish the following Proposition.

**Proposition 1:** With the PS-based EH relay receiver, the conventional three-node EH relay system can achieve a diversity order of two and the high-SNR scaling law of the system outage behavior is jointly determined by \( \log c_0/c_0^2 \), together with \( \log(\log c_0)/c_0^2 \). In particular, an asymptotic outage lower bound can be derived as

\[
P_{\text{out}}^{\text{FixRole, LB}} \simeq \frac{(\tau')^2}{2\sigma_2^2\sigma_1^2} \left(1 - e^{-\frac{\tau'}{\sigma_2^2}} - \frac{C_{\text{Euler}}}{\eta\sigma_2^2} + \frac{1}{2\eta\sigma_2^2}\right)
\]

\[
-\frac{1}{\eta\sigma_2^2} \ln\left(k_0 + \frac{1}{2\sigma_2^2}\right) - \frac{1}{\eta\sigma_2^2} + \left(1 + \frac{k_0}{\eta\sigma_2^2} - e^{-\frac{\tau'}{\sigma_2^2}}\right) \ln\tau' - \zeta, \tag{9}
\]

where \( \zeta = \frac{1}{\eta\sigma_2^2} \ln(-\ln \tau') \).

**Proof:** From the above analysis, (9) can be readily attained. To determine the system diversity order, we apply the well-known lower-bound inequality [14] to the received SNR at the destination, i.e.,

\[
P_{\text{out}}^{\text{FixRole}} \geq \frac{\tau'}{c_0^2} (\tilde{g}_{13} + g_{12} \min[\tilde{g}_{23}, 1]),
\]

to attain \( P_{\text{out}}^{\text{FixRole, LB}} = P_{\text{out}}^{\text{FixRole}} s.t. \tau' = 2\tau' \). Then, with the aid of the pinching theorem, we can deduce that the system diversity order is two. Knowing that \( (\tau')^2 = o((\tau')^2 \ln \tau') \) and \( (\tau')^2 \ln(-\ln \tau') = o((\tau')^2 \ln \tau') \), the scaling law of outage behavior can be readily characterized.

**Remark 1:** It is noticed that the outage probability of the EH relay system under study is dominated by the scaling law of \( (\log c_0)/c_0^2 \) at high SNR, which is similar to the decode-and-forward (DF) case [18]. Nonetheless, unlike the DF case, the scaling law of the AF case is also affected by the term \( \log(\log c_0)/c_0^2 \). In particular, the term regarding \( \log(\log c_0)/c_0^2 \) cannot be omitted in order to maintain a higher accuracy.

To confirm this observation, Fig. 1 shows the asymptotic curves given by Proposition 1, and the numerical results with the term \( \zeta \) omitted in (9) are also plotted for comparisons. From the figure, it is clear that in order to preserve the accuracy of the asymptote, the term regarding \( \log(\log c_0)/c_0^2 \) cannot be discarded. In particular, note that if the term \( \zeta \) is omitted, the ensuing asymptotic result will not be as an asymptotic lower bound any more, as shown in Fig. 1.

**IV. ASYMPTOTIC OUTAGE PROBABILITY OF THE DYNAMIC ROLE CONFIGURATION**

Given (4), an outage lower bound of the EH ROSE cooperative system can be formulated as

\[
P_{\text{out}}^{\text{ROSE}} = \Pr \left(1 + \gamma_{D}^{\text{ROSE}} < R_0\right) \geq \Pr \left(\gamma_{D}^{\text{ROSE}} < \tau\right)
\]

\[
= \Pr \left(\max[\tilde{g}_{13} + \tilde{g}_{12}(1 - \rho) \min[\tilde{g}_{23}, 1], \tilde{g}_{12} + \tilde{g}_{13}(1 - \rho) \times \min[\tilde{g}_{23}, 1], \tilde{g}_{23} + \tilde{g}_{12}(1 - \rho) \min[\tilde{g}_{23}, 1], \tilde{g}_{23} + \tilde{g}_{13}(1 - \rho) \min[\tilde{g}_{23}, 1]] < \tau\right) \triangleq P_{\text{out}}^{\text{ROSE, LB}} \tag{10}
\]

Next, exploiting the relationship among the variables \( \tilde{g}_{12}, \tilde{g}_{13}, \tilde{g}_{23}, \) and \( 1/\tilde{\eta} \), a tight outage lower bound \( P_{\text{out}}^{\text{ROSE, LB}} \) can be
written as
\[ F_{\text{ROSE, LB}}^{\text{ROSE}} = \frac{8}{\sum_{j=1}^{\eta} \text{Pr} \{ \text{Case } j \}, i_j} \]
where Case 1 ~ Case 8 satisfy \{ \hat{g}_{12} < 1/\eta, \hat{g}_{13} < 1/\eta, \hat{g}_{23} < 1/\eta \}, \{ \text{Case 2} \hat{g}_{12} < 1/\eta, \hat{g}_{13} < 1/\eta, \hat{g}_{23} < 1/\eta \},
\{ \text{Case 4} \hat{g}_{12} < 1/\eta, \hat{g}_{13} < 1/\eta, \hat{g}_{23} < 1/\eta \}, \{ \text{Case 6} \hat{g}_{12} \geq 1/\eta, \hat{g}_{13} < 1/\eta, \hat{g}_{23} < 1/\eta \}, \{ \text{Case 7} \hat{g}_{12} \geq 1/\eta, \hat{g}_{13} \geq 1/\eta, \hat{g}_{23} < 1/\eta \}, \{ \text{Case 8} \hat{g}_{12} \geq 1/\eta, \hat{g}_{13} \geq 1/\eta, \hat{g}_{23} \geq 1/\eta \}. In what follows, we focus on the analysis of \( I_1 \), which can be rewritten as
\[ I_1 = \int_{D_{xy}} f_{\hat{g}_{12}}(x) f_{\hat{g}_{13}}(y) \times \text{Pr} \left( \hat{g}_{23} < \min \left[ \frac{\tau' - y}{v\eta}, \frac{\tau' - x}{v\eta} \right], \hat{g}_{23} < \tau' - vxy \right) dx dy \]
where \( v \triangleq (1 - \rho)\hat{\eta} \) and \( D_{xy} \triangleq \{ x < \min[\tau', 1/\eta], y < \min[\tau', 1/\eta], xy < \tau'/v \} \). To solve (12), we need to consider two possible cases: \{ \tau' \geq 1/\eta \} and \{ \tau' < 1/\eta \}, which makes \( D_{xy} \) evolve into two integral domains: \( D_{xy} = \{ x < 1/\eta, y < \tau' \} \) and \( D_{xy} = \{ x < \tau', y < \tau', xy < \tau'/v \} \), respectively. Unfortunately, for either case, the ensuing integral does not admit a closed-form result. Nonetheless, in what follows we will concentrate on the high-SNR regime. At high SNR, the integral domain \( D_{xy} \) degenerates into \( D_{xy} \), and \( \xi \) reduces to \( \xi = \text{Pr} \left( \hat{g}_{23} < \frac{1}{\eta} \min \left[ \frac{\tau' - y}{v}, \frac{\tau' - x}{v} \right], \hat{g}_{23} < \tau' - vxy \right) \).

Note that solving (12) is still a challenging problem. To proceed, we further subdivide the integral domains to simplify the function \( \xi \), which is formulated as below:
\[ \xi = \begin{cases} 1 - e^{-\frac{\tau' - vxy}{\tau' - vxy}}, & \text{if } (x, y) \in \{ A_1' \cup A_2' \cup B_1' \cup B_2' \}, \\ 1 - e^{-\frac{\tau' - vxy}{\tau' - vxy}}, & \text{if } (x, y) \in \{ A_1' \cup A_2' \}, \\ 1 - e^{-\frac{\tau' - vxy}{\tau' - vxy}}, & \text{if } (x, y) \in \{ B_1' \cup B_2' \}, \end{cases} \]
where we have
\[ A_1' \triangleq \{ (x, y) \mid \hat{D}_{xy}, x + y \geq \tau', y \geq x, \tau' \geq y(1 + vx) \geq 0 \}, \]
\[ A_1' \triangleq \{ (x, y) \mid \hat{D}_{xy}, x + y \geq \tau', y \geq x, \tau' \geq y(1 + vx) < 0 \}, \]
\[ A_2' \triangleq \{ (x, y) \mid \hat{D}_{xy}, x + y \geq \tau', y < x, \tau' \geq y(1 + vx) \geq 0 \}, \]
\[ A_2' \triangleq \{ (x, y) \mid \hat{D}_{xy}, x + y \geq \tau', y < x, \tau' \geq y(1 + vx) < 0 \}, \]
\[ B_1' \triangleq \{ (x, y) \mid \hat{D}_{xy}, x + y \geq \tau', y \geq x, \tau' \geq x(1 + vy) \geq 0 \}, \]
\[ B_1' \triangleq \{ (x, y) \mid \hat{D}_{xy}, x + y \geq \tau', y \geq x, \tau' \geq x(1 + vy) < 0 \}, \]
\[ B_2' \triangleq \{ (x, y) \mid \hat{D}_{xy}, x + y \geq \tau', y < x, \tau' \geq x(1 + vy) \geq 0 \}, \]
\[ B_2' \triangleq \{ (x, y) \mid \hat{D}_{xy}, x + y \geq \tau', y < x, \tau' \geq x(1 + vy) < 0 \}. \]

Based on (13), the integral \( I_1 \) in (12) can be divided into two parts, i.e., \( I_1 = I_1^{(1)} + I_1^{(2)} \), where we have
\[ I_1^{(1)} = \int_{A_1'} f_{\hat{g}_{12}}(x) f_{\hat{g}_{13}}(y) \times \left( 1 - e^{-\frac{\tau' - vxy}{\tau' - vxy}} \right) dx dy, \]
\[ I_1^{(2)} = \int_{A_1' \cup A_2' \cup B_1' \cup B_2'} f_{\hat{g}_{12}}(x) f_{\hat{g}_{13}}(y) \xi(x, y) dx dy. \]

By invoking the symmetry of the integrated function with respect to the variates \( x \) and \( y \), \( I_1^{(1)} \) can be re-expressed as
\[ I_1^{(1)} = w_1 + w_2 + w_3|_{\hat{g}_{12} \rightarrow \hat{g}_{13}} + w_4|_{\hat{g}_{12} \rightarrow \hat{g}_{13}}. \]
In which \( w_1 = \int_{A_1'} f_{\hat{g}_{12}}(x) f_{\hat{g}_{13}}(y) \left( 1 - e^{-\frac{\tau' - vxy}{\tau' - vxy}} \right) dx dy \)
and \( w_2 = \int_{A_1'} f_{\hat{g}_{12}}(x) f_{\hat{g}_{13}}(y) \left( 1 - e^{-\frac{\tau' - vxy}{\tau' - vxy}} \right) dx dy \).

In order to characterize the asymptotic behavior of (16), the high-SNR scaling law of \( w_1 \) and \( w_2 \) should be determined. To this end, we rewrite \( w_1 \) as
\[ w_1 = \int_{A_1'} f_{\hat{g}_{12}}(x) f_{\hat{g}_{13}}(y) dx dy \]
\[ \frac{w_{11}}{w_{12}} = \int_{A_1'} f_{\hat{g}_{12}}(x) f_{\hat{g}_{13}}(y) e^{-\frac{\tau' - vxy}{\tau' - vxy}} dx dy. \]
Note that it is infeasible to perform asymptotic analysis directly from the above two-fold integrals. As a remedy, we first develop \( w_{11} \) and \( w_{12} \) into one-fold integrals and then make use of the differential calculus rule, yielding therefore:
\[ w_{11} \sim \frac{(\tau')^2}{4\sigma_{12}^2} \left[ 1 - \frac{1}{8} \frac{1}{\sigma_{12}^2} - \frac{5}{24} \frac{1}{\sigma_{12}^2} \right] - \frac{\tau'}{2\sigma_{12}^2} (\tau')^3. \]

In the same way, we can attain an asymptotic expression for \( w_{12} \), which by its turn leads to \( w_{12} \sim \frac{(\tau')^3}{\sigma_{12}^2 \sigma_{13}^2 \sigma_{23}}. \) Similarly, we can develop an asymptotic expression for \( w_2 \) as \( w_2 \sim \frac{(\tau')^2}{\sigma_{12}^2 \sigma_{13}^2 \sigma_{23}}. \) As thus, \( I_1^{(1)} \) can be asymptotically expressed as
\[ I_1^{(1)} \sim \frac{(\tau')^3}{\sigma_{12}^2 \sigma_{13}^2 \sigma_{23}}, \]
Next, we characterize the asymptotic behavior of \( I_1^{(2)} \). Owing to the symmetry, \( I_1^{(2)} \) can be rearranged as
\[ I_1^{(2)} = \Theta_1 + \Theta_1|_{\hat{g}_{12} \rightarrow \hat{g}_{13}}, \]
where \( \Theta_1 = \int_{A_1'} f_{\hat{g}_{12}}(x) f_{\hat{g}_{13}}(y) \left( 1 - e^{-\frac{\tau' - vxy}{\tau' - vxy}} \right) dx dy. \) In
In this Section, for the benchmark case of fixed role configuration, \( N_1 \) is designated as the source, \( N_2 \) as the relay, and \( N_3 \) as the destination. In addition, throughout this section, the path loss exponent is set to \( m = 2.7 \), as in [5].

Figs. 2 and 3 show the system outage performance of the fixed role configuration as well as the dynamic role configuration, both with the PS-based EH relay. As shown in these figures, the asymptotic outage curves of the dynamic role configuration is very tight over the majority of the SNR regions, and the slope of the outage curve is much steeper than that of the fixed role configuration since a higher diversity order can be achieved by ROSE cooperation, as predicted by Proposition 2. Notably, in the medium-to-high SNR regime, the outage curves of the dynamic role configuration no longer vary with the values of \( \eta \) and \( \rho \), which is different from the case of fixed role configuration. This phenomenon indicates that if the ROSE mechanism is incorporated into the conventional three-node cooperative system with wireless powered relay, the PS factor and the energy conversion efficiency at the relay node become unimportant as long as the transmit power at the source node is sufficiently large.

In order to explicitly characterize the benefits of ROSE mechanism, based on Propositions 1 and 2, we define the same as the counterpart with conventional relay node [9].

(2) As indicated by Proposition 2, when the ROSE mechanism is incorporated, the energy conversion efficiency \( \eta \) and PS factor \( \rho \) at the relay become unimportant. This means that one could neglect the impact of the energy conversion efficiency and PS factor within EH-ROSE cooperative systems once the source transmit SNR is sufficiently large.

(3) When the EH relay is deployed instead of the conventional relay with fixed power supply [9, Eq. (13)], the system outage probability is increased doubled. In return, the energy consumption of fixed power supply within ROSE cooperative systems can be reduced by 50\%, since the EH relay node no longer needs to consume its own (fixed) energy supply.

V. NUMERICAL RESULTS AND DISCUSSION

In the following Proposition, we now establish the asymptotic scaling law for the system outage behavior of the EH ROSE cooperative system.

**Proposition 2:** With the PS-based EH receiver at the relay, the ROSE cooperative system can achieve a diversity order of three, with an scaling law of \( 1/c_0^3 \). In particular, a tight outage lower bound can be asymptotically written as

\[
P_{\text{out}}^{\text{ROSE, LB}} \simeq \frac{\tau^3}{c_0^3 \sigma_1^2 \sigma_{13} \sigma_{23}}.
\]

**Proof:** From the preceding results, it is ready to arrive at (25). With regard to the proof of the system diversity order, one can arrive at this result by following a similar procedure as employed in the proof of Proposition 1.

**Remark 2:**

(1) It should be noticed that the ROSE cooperation with EH relay can enhance the system diversity gain to one-order higher than that of the fixed role configuration. This means that the random acquisition of wireless energy can still guarantee a system diversity order of three for ROSE cooperation, being
Fig. 3. Comparisons of fixed role configuration and dynamic ROSE in terms of outage probability in the scenario of PS-based EH relaying ($R_0 = 1$ bit/s/Hz, $\eta = 0.4$, $d_{12} = 0.63$, $d_{13} = 0.52$, and $d_{23} = 0.31$).

Fig. 4. The variation of ROSE gain with respect to the PS factor at the relay ($R_0 = 1$ bit/s/Hz, $d_{12} = 0.5$, $d_{13} = 1$, $d_{23} = 0.5$, and $c_0 = 30$ dB).

ROSE gain of the dynamic role configuration with PS-based EH relay as

$$C_{\text{ROSE}}^{\text{EH}} = 10 \log_{10} \left( \frac{P_{\text{out}}^{\text{ROSE,\infty}}}{P_{\text{out}}^{\text{ROSE,\infty}}} \right)$$

$$\approx 10 \log_{10} \left( \frac{c_0 \sigma_{23}^2}{2\pi \sigma_{12}^2} \right) \left( e^{-\frac{\sigma_{12}^2}{2\sigma_{23}^2}} - \frac{C_{\text{Euler}}}{\eta \sigma_{23}} + \frac{1}{2\eta \sigma_{23}} \ln \left( -\ln \rho \right) \right)$$

where $P_{\text{out}}^{\text{ROSE,\infty}}$ and $P_{\text{out}}^{\text{ROSE,\infty}}$ denote the asymptotic outage probability of fixed role configuration and the dynamic role selection, respectively, both with PS-based EH relay. Fig. 4 shows the ROSE gain of the dynamic role configuration with PS-based EH relay. One important observation is that the ROSE gain increases with a decline in the energy conversion efficiency $\eta$ at the relay. This phenomenon demonstrates that when the energy conversion efficiency at the relay node is low, the ROSE mechanism can produce a more significant improvement of system transmission robustness relative to the fixed role configuration. On the other hand, for any given value of $\eta$, there is always a minimal ROSE gain with regard to the PS factor $\rho$. In particular, either an extremely small or large value of $\rho$ could produce a more considerable ROSE gain.

VI. CONCLUSION

In this paper, we proposed dynamic ROSE mechanism as an effective method of improving the diversity and hence the performance of the conventional EH relay systems. By invoking ROSE mechanism, we analytically showed that a diversity order of three can be achieved, which is one order higher than that of the conventional fixed role configuration EH relay system. Moreover, with ROSE cooperation, the effect of the energy conversion efficiency and the power-splitting factor at the relay become negligible in the medium-to-high SNR regions. Simulations corroborate the analytical claims and verifies the correctness of our analysis.

REFERENCES