On Outage of WPC System with Relay Selection over Nakagami-m Fading Channels

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***Abstract*—This paper considers a dual-hop wireless powered cooperative system with multiple relays, which consists of a source (S), a destination (D) and multiple relay candidates. These relay candidates can harvest energy from the interference signals to transfer the decoded data to D. Two classic relay selection schemes, optimal source-relay link and optimal source-relay-destination link schemes, are considered to choose a best relay to aid the transmission between S and D under conditional decode-and-forward scheme. The closed-form expressions of the outage probability for the two considered relay selection schemes have been derived and verified over independent Nakagami-m fading channels.**

***Index Terms*—Conditional decode-and-forward, energy harvesting, interference, relay selection, outage probability.**

I. Introduction

Over the past years, the terminals in wireless networks, such as cellular networks and wireless sensor networks, are usually powered by batteries, which have a limited energy capacity, and in the presence of a rigid problem to prolong the lifetime. Wireless energy harvesting (EH) technology has been regarded as an efficient and practical way to work with this problem as it allows the terminals to harvest energy from the received signals. Essentially, energy is designed to be transferred via the radio frequency (RF) signal accompanied by information data by using wireless EH technology [1].

So far, there have been two classic approaches proposed to harvest energy: power splitting (PS) [2]-[4], and time switching (TS) [4]-[6]. In most of the existing works, the terminals are planned to harvest energy from the received target signal, while few works has considered to harvest energy from the interference signals, which are quite ubiquitous in practical scenarios as multiple radio systems are coexisted with each other, as well as the co-channel interference arisen by the channel multiplexing technologies, e.g., code division multiple access. In [7], a three-nodes relaying system was considered, where the relay adopts the harvested energy from interferers and the source (S) to forward the received information to the destination (D). Moreover, the outage performance of PS and AS schemes has been analyzed and compared.

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Most works on decode-and-forward (DF) schemes considered that the relays aid the source-destination pair without the direct link between S and D. But if the direct link is good enough, then D can decode the transmitted information correctly and plenty of resource will be wasted. To work with this problem, we consider a conditional DF scheme: D adopts its instantaneous signal-to-interference-plus-noise ratio (SINR) of the received signal over S-D link as an indication of the need of the cooperation aid by R. If the received SINR over S-D link is smaller than a predefined threshold (γ_0), D sends a request to the relay asking it to forward the recoded signal; Otherwise, R remains silent.

In traditional relay schemes, S transmits information to D with the help of the relay. In [8]-[9], the authors proposed a partial relay selection (PRS) scheme for dual-hop fixed-gain relay systems where the optimal source-relay link (OSRL) was employed in the first-hop transmission. Under optimal source-relay-destination link (OSRDL) scheme, the best source-relay-destination link was selected as the data transmission link [10]-[11]. However, none of these works has considered EH in multiple-relay systems.

In this paper, we study the outage performance for two PRS schemes, OSRL and OSRDL, for a wireless powered cooperative (WPC) system over Nakagami-m channels in the presence of multiple jamming interference. Specially, under conditional relay scheme when the transmission over direct S-D link fails, one of N ($N > 1$) relay candidates is selected as the relay, which harvests energy from the jamming signals to forward the decoded information to D. The closed-form expression for the outage probability (OP) of the two considered PRS schemes are derived and verified. To the best of our knowledge, there has no similar work presented in the open literature. Main contributions of this work are: (1) Compared to [7], we consider the EH for multiple-relay selection with direct link; (2) Compared to [8]-[11], we introduce EH to the traditional multiple-relay systems and analyze the outage performance.

II. System model

In this work, we consider a multi-relay cooperative system, consisting of one source (S), one destination (D), N ($N > 1$) relay candidates, while each relay and D are in presence of multiple jamming signals and use the energy harvested from interferers. When the quality of S-D link can not satisfy the requirement of the data transmission, one best relay, R, is selected among these candidates by using OSRL or OSRDL schemes to forward the decoded information to D, and the relay can harvest energy from the interference signals to deliver the information over R-D link. It is assumed that all terminals are with a single transmit and receiving antenna and operate in half-duplex mode. Furthermore, we also assume that all links experience independent and identically distributed quasi-static Nakagami-m fading. In this work, we assume that relay selection process has been conducted before data transmission (The details about the PRS process can be referred to [9]-[11]). Then, under conditional DF scheme, the information transmission process can be divided into two phases;

1) S sends the information to R and D;

2)The received signal at R and D can be given by $y_{sr} = \sqrt{P_s d_{B1}^{-\alpha}} h_{sr} s + \sum_{j=1}^{N_1} \sqrt{Q_j d_{Ir,j}^{-\alpha}} g_j s_j + n_{ra} + n_{rc}$, $y_{sd} = \sqrt{P_s d_{B3}^{-\alpha}} h_{sd} s + \sum_{j=1}^{N_3} \sqrt{Q_{j1} d_{I3,j}^{-\alpha}} g_{j1} s_{j1} + n_{da} + n_{dc}$, respectively, where P_s is the transmit power at S, d_{B1} and d_{B3} denote the distance of S-R and S-D links, respectively, N_1 is the number of interferers at R of S-R link, N_2 is the number of interferers at D of the direct S-D link, respectively, $d_{Ir,j}$ ($j \in \{1, 2, \cdots, N_1\}$) is the distance between the j-th interferer and R, $d_{I3,j}$ ($j \in \{1, 2, \cdots, N_3\}$) is the distance between the j-th interferer and D in the 1st phase, α is the path-loss exponent, h_{mn} ($m, n \in \{s, r, d\}$) is the small-scale fading gain between node m and n, s denotes the transmitted symbols from S, s_j and s_{j1} are the transmitted symbol from S and the j-th interferer, respectively, n_{ra} and n_{da} are the additive white Gaussian noise (AWGN) at the receiver of R and D, respectively, n_{rc} and n_{dc} are the AWGN due to the RF-to-baseband conversion at R and D, respectively, n_{ra} and n_{rc} have zero mean and variances of σ_{ra}^2 and σ_{rc}^2, Q_j and Q_{j1} are the transmiT power of the j-th interferer to R and R, respectively, N_3 is the number of the jamming signals at D, g_j and g_{j1} are the small-scale fading gain of the links from the j-th interferer to R and D in the 1st phase, respectively.

In this paper, Nakagami-m fading is assumed such that $|h_i|^2$ and $|g_j|^2$, $i = 1, 2, 3$, $j = 1, 2, \cdots, N_i$, follow Gamma distributions with probability density functions (PDFs), $f_{|h_i|^2}(x) = \left(\frac{m_i}{\Omega_i}\right)^{m_i} \frac{x^{m_i - 1}}{\Gamma(m_i)} \exp\left(-\frac{m_i}{\Omega_i} x\right)$, $f_{|g_j|^2}(x) = \left(\frac{m_j}{\Omega_j}\right)^{m_j} \frac{x^{m_j - 1}}{\Gamma(m_j)} \exp\left(-\frac{m_j}{\Omega_j} x\right)$, respectively, where m_i and Ω_i are the m parameter and the average fading power in the S-R link, and m_j and Ω_j are the m parameter and the fading power in the link from the N_i interferer to the relay.

Define $\gamma_{sr_k} = \gamma_1, \gamma_{r_k d} = \gamma_2, \gamma_{sd} = \gamma_3$, $k = (1, 2, \cdots, N)$. Therefore, the SINR of the received signal at R and D can be written as $\gamma_1 = \frac{P_s |h_1|^2}{d_{B1}^{\alpha}\left(\sum_{j=1}^{N_1} Q_j d_{Ir,j}^{-\alpha} |g_j|^2 + \sigma_{ra}^2 + \sigma_{rc}^2\right)}$, $\gamma_3 = \frac{P_s |h_3|^2}{d_{B3}^{\alpha}\left(\sum_{j=1}^{N_3} Q_{j1} d_{I3,j}^{-\alpha} |g_{j1}|^2 + \sigma_{da}^2 + \sigma_{dc}^2\right)}$, respectively.

In the 2nd phase, if R forwards the regenerated symbols to D, the received signal at D can be given as $y_{rd} = \sqrt{P_r d_{B2}^{-\alpha}} h_2 s_r + \sum_{j=1}^{N_2} \sqrt{Q_{j2} d_{I2,j}^{-\alpha}} g_{j2} s_{j2} + n_{da1} + n_{dc1}$, where $d_{I2,j}$ ($j \in \{1, 2, \cdots, N_2\}$) is the distance between the j-th interferer and D in the 2nd phase, s_{j2} is the transmitted symbol from the j-th interferer, Q_{j2} is the transmit power at the j-th interferer, N_3 is the number of the interferers at D. These interferer parameters of S-D link may be different from R-D's, as they're time-varying. $P_r = \theta\eta \sum_{j=1}^{N_1} Q_j d_{I2,j}^{-\alpha} |g_j|^2$, where θ is the time duration ratio of the S-R and R-D transmissions, η is the conversion efficiency of the energy harvester at the relay.

Therefore, the SINR of the received signal at D can be written as $\gamma_2 = \frac{P_r |h_2|^2}{d_{B2}^{\alpha}\left(\sum_{j=1}^{N_2} Q_{j2} d_{I2,j}^{-\alpha} |g_{j2}|^2 + \sigma_{da1}{}^2 + \sigma_{dc1}{}^2\right)}$.

In the following, we assume the distances among all interferers and R and D are same during each phase, namely, $d_{Ir,j} = d_{Ir}$, $d_{I3,j} = d_{I3}$, $d_{I2,j} = d_{I2}$, and all interfering channel gains obey a same Nakagmi-m distribution with (m_{I1}, Ω_{I1}), (m_{I3}, Ω_{I3}), and (m_{I2}, Ω_{I2}), respectively, during each phase for simplification.

III. Outage Probability

A. Cumulative distribution functions (CDFs) of γ_{sd}, γ_{sr} and γ_{rd}

Define $Y_1 = \sum_{j=1}^{N_1} Q_j d_{Ir,j}^{-\alpha} |g_j|^2$ and $Y_3 = \sum_{j=1}^{N_3} Q_{j1} d_{I3,j}^{-\alpha} |g_{j1}|^2$. The PDF of Y_1 and Y_3 can be derived by equation ([7], (27)).

Therefore, the PDF of γ_1 and γ_3 can be presented as

$$f_{\gamma_1}(\gamma_1) = B_1 d_{B1}^{m_1 \alpha} \times \sum_{r=0}^{N_{I1}-1} \binom{N_{I1} - 1}{r} \gamma_1^{m_1 - 1} (-n_r)^r p_{I1}^{N_{I1}} \times \left(\frac{d_{B1}^{\alpha} m_1 \gamma_1}{\Omega_1 P_s} + p_{I1}\right)^{r - N_{I1} - m_1} (N_{I1} - 1 - r + m_1)! \quad (1)$$

and

$$f_{\gamma_3}(\gamma_3) = B_3 d_{B3}^{m_3 \alpha} \times \sum_{r=0}^{N_{I3}-1} \binom{N_{I3} - 1}{r} \gamma_3^{m_3 - 1} (-n_d)^r p_{I3}^{N_{I3}} \times \left(\frac{d_{B3}^{\alpha} m_3 \gamma_3}{\Omega_3 P_s} + p_{I3}\right)^{r - N_{I3} - m_3} (N_{I3} - 1 - r + m_3)!, \quad (2)$$

respectively, $B_1 = \frac{\left(\frac{m_1}{\Omega_1}\right)^{m_1} e^{p_{I1} n_r}}{\Gamma(m_1) {P_s}^{m_1} \Gamma(N_{I1})}$, $B_3 = \frac{\left(\frac{m_3}{\Omega_3}\right)^{m_3} e^{p_{I3} n_d}}{\Gamma(m_3) {P_s}^{m_3} \Gamma(N_{I3})}$, $p_{Ii} = \frac{m_{Ii} d_{Ii}^{\alpha}}{Q_{Ii} \Omega_{Ii}}$, $N_{Ii} = m_{Ii} N_i$, $i = \{1, 2, 3\}$, $n_r = \sigma_{ra}^2 + \sigma_{rc}^2$, $n_d = \sigma_{da}^2 + \sigma_{dc}^2$, $\binom{k}{l} = \frac{k!}{l!(k-l)!}$ is the binomial coefficient, ${}_2F_1(a, b; c; z)$ is the Gaussian hypergeometric function.

Therefore, the CDF of γ_1 and γ_3 can be derived as

$$F_{\gamma_1}(\gamma_1) = B_1 \times \frac{(d_{B1}^{\alpha} \gamma_1)^{m_1}}{m_1} \sum_{r=0}^{N_{I1}-1} p_{I1}^{r - m_1} (-n_r)^r \times \binom{N_{I1} - 1}{r} p_{I1}^{r - m_1} (N_{I1} - 1 - r + m_1)! \times {}_2F_1\left(N_{I1} + m_1 - r, m_1; 1 + m_1; \frac{-m_1 d_{B1}^{\alpha}}{p_{I1} \Omega_1 P_s} \gamma_1\right) \quad (3)$$

and

$$F_{\gamma_3}(\gamma_3) = B_3 \times \frac{(d_{B3}^{\alpha} \gamma_3)^{m_3}}{m_3} \sum_{r=0}^{N_{I3}-1} p_{I3}^{r - m_3} (-n_d)^r \times \binom{N_{I3} - 1}{r} p_{I3}^{r - m_3} (N_{I3} - 1 - r + m_3)! \times {}_2F_1\left(N_{I3} + m_3 - r, m_3; 1 + m_3; \frac{-m_3 d_{B3}^{\alpha}}{p_{I3} \Omega_3 P_s} \gamma_3\right), \quad (4)$$

respectively. The derivations of (1) and (3) can be found in Appendix. The derivations of (2) and (4) are similar to the ones of (1) and (3).

Define $Y_2 = \sum_{j=1}^{N_2} Q_{j2} d_{I2,j}^{-\alpha} |g_{j2}|^2$, $n_3 = {\sigma_{da1}}^2 + {\sigma_{dc1}}^2$. Similarly, the PDF of Y_2 can be derived by equation ([7], (27)).

The PDF of P_r can be written as $f_{P_r}(x) = p_{I1}^{N_{I1}} \frac{\exp\left(\frac{x}{\eta} p_{I1}\right) x^{N_{I1}-1}}{\Gamma(N_{I1}) \eta^{N_{I1}} \theta^{N_{I1}}}$.

Then, the PDF and CDF of γ_2 can be presented as (5) and (6), respectively, as shown on the top of next page, where $C_2 = \frac{p_{I1} m_2 (d_{B2}^{\alpha} \gamma_2)^{\frac{N_{I1}+m_2+1}{2}}}{p_{I2} \eta \Omega_2 \Gamma(m_2+N_{I2}-q) \Gamma(N_{I1}+N_{I2}-q)}$, $\mathrm{W}_{a,b}(x)$ is the Whittaker Function, $\Gamma\left(\begin{array}{c} a \\ b \end{array}\right) = \frac{\Gamma(a)}{\Gamma(b)}$, $G_{p,q}^{m,n}\left[z \middle| \begin{array}{c} a_1, \cdots, a_p \\ b_1, \cdots, b_q \end{array}\right]$ is the Meijer Function, λ is as shown on the top of next page. The derivations of the PDF and CDF of γ_2 can be found in Appendix.

B. Outage probability of OSRL scheme

The output SINR of the combiner can expressed as $\gamma_D = \begin{cases} \gamma_3, & \gamma_3 > \gamma_0 \\ \max\{\gamma_{eq}, \gamma_3\}, & \gamma_3 \le \gamma_0 \end{cases}$, where $\gamma_{eq} = \min\{\gamma_{sr}, \gamma_2\}$.

Under OSRL scheme, the relay with the maximum SINR among S-R links is selected [8]-[11], $\gamma_{sr} = \max\{\gamma_{srk}\}$. The CDF of γ_{sr} and γ_{eq} can expressed as $F_{\gamma_{sr}}(\gamma_{sr}) = [F_{\gamma_1}(\gamma_{srk})]^N$ and $F_{\gamma_{eq}}(\gamma_{eq}) = F_{\gamma_{sr}}(\gamma_{eq}) + F_{\gamma_2}(\gamma_{eq}) - F_{\gamma_{sr}}(\gamma_{eq}) F_{\gamma_2}(\gamma_{eq})$.

Thus, the OP for OSRL scheme can be expressed as

$$\begin{aligned} \mathrm{P_{out}}(\gamma_{\mathrm{d}} < \gamma_{\mathrm{th}}) &= \mathrm{P}\{\gamma_3 \le \gamma_0\} \mathrm{P}\{\max\{\gamma_{eq}, \gamma_3\} \le \gamma_{th} | \gamma_3 \le \gamma_0\} \\ &\quad + \mathrm{P}\{\gamma_3 > \gamma_0\} \mathrm{P}\{\gamma_3 \le \gamma_{th} | \gamma_3 > \gamma_0\} \\ &= \mathrm{P}\{\gamma_{eq} \le \gamma_{th}, \gamma_3 \le \min\{\gamma_{th}, \gamma_0\}\} \\ &\quad + \mathrm{P}\{\gamma_0 < \gamma_3 \le \gamma_{th}\}. \end{aligned} \tag{8}$$

where γ_{th} is the threshold SINR for outage events.

Finally, we can derived the OP for OSRL as

$$\begin{aligned} &\mathrm{P_{out}}(\gamma_{\mathrm{d}} < \gamma_{\mathrm{th}}) \\ &= \begin{cases} F_{\gamma_{eq}}(\gamma_{th}) F_{\gamma_3}(\min\{\gamma_{th}, \gamma_0\}) \\ + F_{\gamma_3}(\gamma_{th}) - F_{\gamma_3}(\gamma_0), & \gamma_{th} > \gamma_0 \\ F_{\gamma_{eq}}(\gamma_{th}) F_{\gamma_3}(\min\{\gamma_{th}, \gamma_0\}), & \gamma_{th} \le \gamma_0 \end{cases} \end{aligned} \tag{9}$$

C. Outage probability of OSRDL scheme

Under OSRDL scheme, the relay is chose according to the following rule [10]-[11], $\gamma_{eq} = \max\{\min\{\gamma_1, \gamma_2\}\}$, the CDF of which can be written as $F_{\gamma_{eq}}(x) = [F_{\gamma_1}(x) + F_{\gamma_2}(x) - F_{\gamma_1}(x) F_{\gamma_2}(x)]^N$.

Similarly, the OP for OSRDL scheme can be expressed as Eq. (9).

IV. Numerical results and discussions

For simplification, in this section we use Ω_1, Ω_2, Ω_3, Ω_{I1}, Ω_{Ij}, m_1, m_2, m_3, m_{I1} and m_{Ij} to denote Ω_{srk}, Ω_{rkd}, Ω_{sd}, Ω_{jr}, Ω_{jd}, m_{srk}, m_{rkd}, m_{sd}, m_{jr} and m_{jd}, respectively. Unless otherwise explicitly specified, the main parameters used in simulation and analysis are set as $m_1 = 1$, $m_2 = 10$ dB, $m_3 = 1$ dB, $m_{I1} = m_{I2} = m_{I3} = 2$ dB, $\Omega_1 = 1$ dB, $\Omega_2 = 10$ dB, $\Omega_3 = 1$ dB, $Q_D = 0.8$ dB, $\Omega_{I1} = \Omega_{I2} = \Omega_{I3} = 2$ dB, $\gamma_0 = 2$ dB, $N = 3$, $Q_R = 2$ dB, $N_1 = N_2 = N_3 = 5$, $n_r = n_d = n_3 = 1$, $d_{B1} = d_{B2} = d_{B3} = 3$ m, $d_{Ir} = d_{I3} = d_{I2} = 2$ m, $\alpha = 2$, $\theta = 1$ and $\eta = 0.4$.

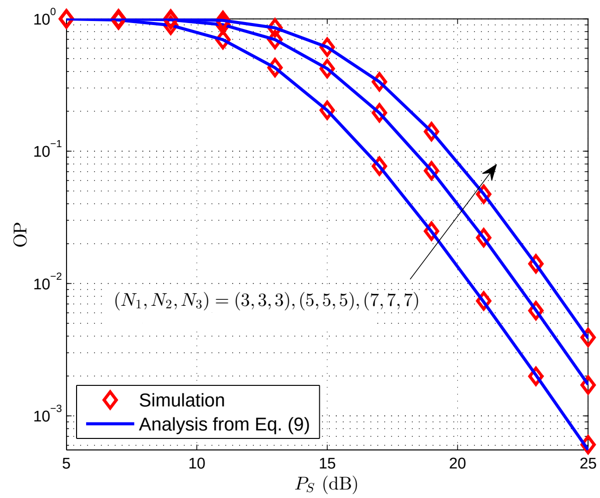

Fig. 1. OP vs. P_S for $OSRL$ scheme

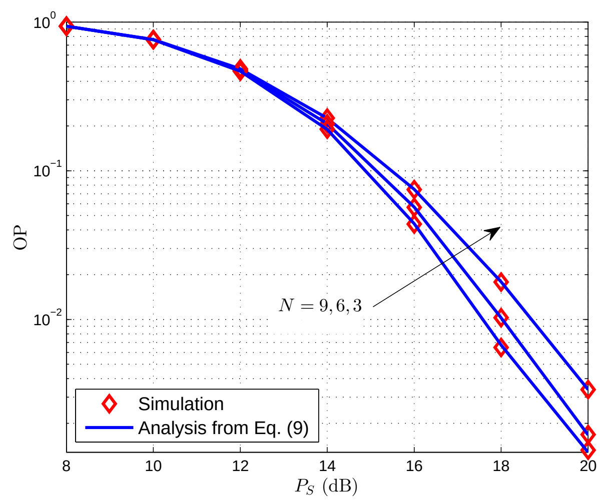

Fig. 2. OP vs. P_S for $OSRL$ scheme

In Figs. 1-4, we present simulation and analytical results for the OP of the two schemes under both OSRL and OSRDL schemes against P_S for various N and various combines of (N_1, N_3, N_2). It can be observed in these figures that there is an excellent agreement among simulation and analytical results, confirming the correctness of our proposed analytical models.

In Figs. 1 and 3, where $\gamma_{th} = 3$ dB, we can see that OP gets worse with the increasing of the number of interferences. It can be explained by the fact that increasing the number of interference means that S-R, S-D and R-D links are getting worse when they are with a same transmit power.

In Figs. 2 and 4, where $\gamma_{th} = 1$ dB, we examine the effect of the number of relays on OP performance. Clearly, the OP under OSRL and OSRDL schemes can be improved when the number of relays increases because of a larger number of

$$f_{\gamma_2}(\gamma_2) = \lambda \times d_{B2}^{\alpha} \exp\left(\frac{p_{I1}m_2\gamma_2}{2p_{I2}\Omega_2\eta}d_{B2}^{\alpha}\right)(d_{B2}^{\alpha}\gamma_2)^{\frac{N_{I1}+m_2-3}{2}} \mathrm{W}_{\frac{1-N_{I1}-m_2-2N_{I2}+2q}{2},\frac{N_{I1}-m_2}{2}}\left(\frac{p_{I1}m_2\gamma_2}{p_{I2}\Omega_2\eta}d_{B2}^{\alpha}\right) \tag{5}$$

$$F_{\gamma_2}(\gamma_2) = \lambda \times C_2 \times G_{2,3}^{2,2}\left[\frac{p_{I1}m_2}{\eta\Omega_2}d_{B2}^{\alpha}\gamma_2\middle| \begin{matrix} -\frac{N_{I1}+m_2-1}{2}, \frac{1-N_{I1}-m_2-2N_{Ij}+2q}{2} \\ -\frac{N_{I1}-m_2+1}{2}, \frac{N_{I1}-m_2-1}{2}, -\frac{N_{I1}+m_2+1}{2} \end{matrix}\right] \tag{6}$$

$$\lambda = \frac{p_{I2}^{\frac{1-N_{I1}-m_2+2q}{2}}\left(\frac{m_2}{\Omega_2}\right)^{m_2}p_{I1}^{N_{I1}}e^{p_{I2}n_3}}{\sqrt{\frac{m_2p_{I1}}{\Omega_2\eta}}\Gamma(m_2)\Gamma(N_{I1})\eta^{N_{I1}}\Gamma(N_{I2})}\left(\frac{\eta m_2}{p_{I1}\Omega_2}\right)^{\frac{N_{I1}-m_2}{2}}\sum_{q=0}^{N_{I2}-1}\binom{N_{I2}-1}{q}(-n_3)^q\Gamma(N_{I1}+N_{I2}-q)\Gamma(N_{I2}-q+m_2) \tag{7}$$

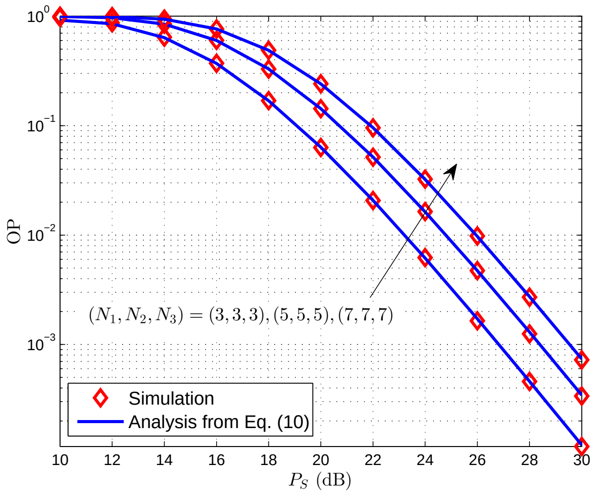

Fig. 3. OP vs. P_S for $OSRDL$ scheme

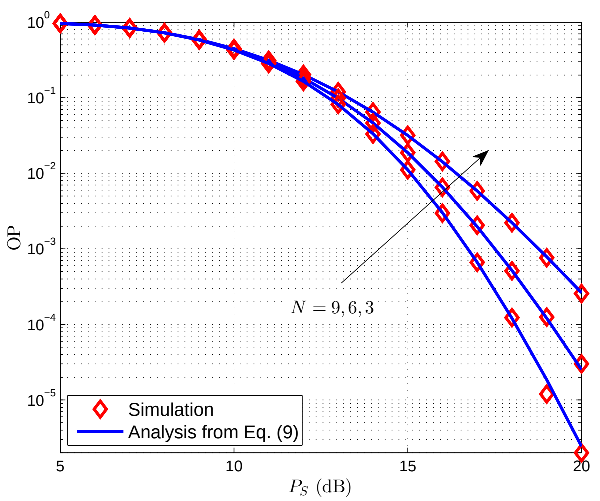

Fig. 4. OP vs. P_S for $OSRDL$ scheme

relays representing a higher diversity gain.

V. Conclusion

In this paper, we have investigated the outage performance of wireless powered conditional cooperative systems with two PRS schemes over independent Nakagami-m fading channels. The relays are considered to harvest energy from the neighboring interference signals to forward the decoded information to the destination. The closed-form expressions for OP have been derived for both OSRL and OSRDL schemes while considering multiple interferences at the relays and destination, respectively. The simulation results show excellent agreement with the analytical ones obtained from our proposed analytical models.

VI. Appendix

A. Derivation of (1) and (3)

Define $x_1 = P_s|h_1|^2$, $y_1 = Y_1 - n_r$. Then, γ_1 can be expressed as $\gamma_1 = \frac{x_1}{y_1}$. Using (3), (9), and ([12], 6.60), we can derived the PDF as

$$\begin{aligned} f_{\gamma_1}(\gamma_1) &= d_{B1}^{\alpha}\int_0^{\infty} y_1 f_{x_1}(y_1 d_{B1}^{\alpha}\gamma_1) f_{y_1}(y_1) dy \\ &= B_1 \times (d_{B1}^{\alpha}\gamma_1)^{m_1-1}\int_0^{\infty} y_1^{m_1}(y_1-n_r)^{N_{I1}-1} \\ &\quad \times \exp\left(-p_{I1}(y_1-n_r) - \frac{m_1\gamma_1}{\Omega_1 P_s}d_{B1}^{\alpha}y_1\right)dy_1. \end{aligned} \tag{10}$$

where $(y_1 - n_r)^{N_{I1}-1}$can be written as

$$(y_1-n_r)^{N_{I1}-1} = \sum_{r=0}^{N_{I1}-1}\binom{N_{I1}-1}{r}y_1^{N_{I1}-1-r}(-n_r)^r. \tag{11}$$

Using (28) in (27), we can derive f_{γ_1} as

$$\begin{aligned} f_{\gamma_1}(\gamma_1) &= d_{B1}^{m_1\alpha}B_1 \times \gamma_1^{m_1-1}\sum_{r=0}^{N_{I1}-1}\binom{N_{I1}-1}{r}(-n_r)^r \\ &\quad \times \int_0^{\infty} y_1^{N_{I1}-1-r+m_1}\exp\left(-\left(p_{I1}+\frac{m_1 d_{B1}^{\alpha}\gamma_1}{\Omega_1 P_s}\right)y_1\right)dy_1. \end{aligned} \tag{12}$$

Using ([13], 3.351.4), f_{γ_1} can be further rewritten as

$$f_{\gamma_1}(\gamma_1) = d_{B1}^{m_1\alpha} B_1 \times \gamma_1^{m_1-1} \sum_{r=0}^{N_{I1}-1} \binom{N_{I1}-1}{r} (-n_r)^r \times \left(d_{B1}^{\alpha} \frac{m_1\gamma_1}{\Omega_1 P_s} + p_{I1} \right)^{r-N_{I1}-m_1} (p_{I1}-1-r+m_1)!. \quad (13)$$

The CDF of γ_1, $F_{\gamma_1}(\gamma_1) = \int_0^{\gamma_1} f_{\gamma_1}(\gamma_1)d\gamma_1$, can be expressed as

$$\begin{aligned} F_{\gamma_1}(\gamma_1) &= B_1 \times \sum_{r=0}^{N_{I1}-1} \binom{N_{I1}-1}{r} (p_{I1}-1-r+m_1)!(-n_r)^r \\ &\times \int_0^{\gamma_1} \left(d_{B1}^{\alpha} \frac{m_1\gamma_1}{\Omega_1 P_s} + p_{I1} \right)^{r-N_{I1}-m_1} (d_{B1}^{\alpha}\gamma_1)^{m_1-1} d\gamma_1 \\ &= B_1 d_{B1}^{m_1\alpha} \times \sum_{r=0}^{N_{I1}-1} \binom{N_{I1}-1}{r} (p_{I1}-1-r+m_1)! \\ &\cdot (-n_r)^r \times \int_0^{\gamma_1} \frac{\gamma_1^{m_1-1}}{\left(\frac{d_{B1}^{\alpha} m_1\gamma_1}{p_{I1}\Omega_1 P_s}+1\right)^{N_{I1}+m_1-r}} d\gamma_1. \end{aligned} \quad (14)$$

Using ([13], 3.194.1), $F_{\gamma_1}(\gamma_1)$ can be rewritten as

$$\begin{aligned} F_{\gamma_1}(\gamma_1) = B_1 \times &\sum_{r=0}^{N_{I1}-1} (-n_r)^r \binom{N_{I1}-1}{r} \\ &\times p_{I1}^{r-m_1} (N_{I1}-1-r+m_1)! \\ &\times {}_2F_1 \left(p_{I1}+m_1-r, m_1; 1+m_1; -\frac{m_1\gamma_1}{p_{I1}P_s} d_{B1}^{\alpha} \right). \end{aligned} \quad (15)$$

B. Derivation of (5) and (6)

Define $x_2 = P_r|h_2|^2$, $Y_2 = \sum_{j=1}^{N_2} Q_{j2} d_{I2,j}^{-\alpha} |g_{j2}|^2$, $y_2 = Y_2 - n_3$, $P_r = \eta Y_1$, the PDF of x_2 can be expressed as

$$\begin{aligned} f_{x_2}(x_2) &= \int_0^{\infty} \frac{1}{P_r} f_{|h_2|^2}\left(\frac{x_2}{P_r}\right) f_{P_r}(P_r) dP_r \\ &= \frac{x_2^{m_2-1}\left(\frac{m_2}{\Omega_2}\right)^{m_2} p_{I1}^{N_{I1}}}{\Gamma(m_2)\Gamma(N_{I1})\eta^{N_{I1}}} \\ &\times \int_0^{\infty} P_r^{N_{I1}-1-m_2} \exp\left(\frac{-p_{I1}}{\eta} P_r - \frac{m_2 x_2}{\Omega_2 P_r} \right) dP_r. \end{aligned} \quad (16)$$

Using ([13], 3.471.9), $f_{x_2}(x_2)$ can be further written as

$$\begin{aligned} f_{x_2}(x_2) &= \frac{2\left(\frac{m_2}{\Omega_2}\right)^{m_2} p_{I1}^{N_{I1}}}{\Gamma(m_2)\Gamma(N_{I1})\eta^{N_{I1}}} \left(\frac{\eta m_2}{p_{I1}\Omega_2}\right)^{\frac{N_{I1}-m_2}{2}} \\ &\times K_{N_{I1}-m_2}\left(2\sqrt{\frac{p_{I1}m_2}{\eta\Omega_2}x_2} \right) x_2^{\frac{N_{I1}+m_2}{2}-1}. \end{aligned} \quad (17)$$

Using ([12], 6.60), the PDF of γ_2 can be derived as

$$\begin{aligned} f_{\gamma_2}(\gamma_2) &= d_{B2}^{\alpha} \int_0^{\infty} y_2 f_{x2}(y_2 d_{B2}^{\alpha}\gamma_2) f_{y_2}(y_2) dy_2 \\ &= 2E_2 \times d_{B2}^{\alpha\frac{N_{I1}+m_2}{2}} \gamma_2^{\frac{N_{I1}+m_2}{2}-1} \sum_{q=0}^{N_{I2}-1} \binom{N_{I2}-1}{q} \\ &\times (-n_3)^q \int_0^{\infty} K_{N_{I1}-m_2}\left(2\sqrt{\frac{p_{I1}m_2}{\eta\Omega_2} y_2 d_{B2}^{\alpha}\gamma_2} \right) \\ &\times e^{-p_{I2}y_2} y_2^{\frac{N_{I1}+m_2+2N_{I2}-2-2q}{2}} dy_2, \end{aligned} \quad (18)$$

where $E_2 = \frac{(\frac{m_2}{\Omega_2})^{m_2} p_{I1}^{N_{I1}} e^{p_{I2}n_3}}{\Gamma(m_2)\Gamma(N_{I1})\eta^{N_{I1}}\Gamma(N_{I2})} p_{I2}^{N_{I2}} \left(\frac{\eta m_2}{p_{I1}\Omega_2}\right)^{\frac{N_{I1}-m_2}{2}}$, $K_v(z)$ is the Modified Bessel function of second kind.

Define $y = y_2^2$ and using [14], we can have

$$\begin{aligned} f_{\gamma_2}(x) &= \lambda \times d_{B2}^{\alpha\frac{N_{I1}+m_2-1}{2}} \exp\left(\frac{p_{I1}m_2 x}{2p_{I2}\Omega_2\eta} d_{B2}^{\alpha} \right) x^{\frac{N_{I1}+m_2-3}{2}} \\ &\times \mathrm{W}_{\frac{1-N_{I1}-m_2-2N_{I2}+2q}{2}, \frac{N_{I1}-m_2}{2}} \left(\frac{p_{I1}m_2 x}{p_{I2}\Omega_2\eta} d_{B2}^{\alpha} \right). \end{aligned} \quad (19)$$

Similarly, the CDF of γ_2 can be derived as

$$\begin{aligned} F_{\gamma_2}(z) &= \int_0^z f_{\gamma_2}(x)dx \\ &= \lambda \times d_{B2}^{\alpha\frac{N_{I1}+m_2-1}{2}} \int_0^z \exp\left(\frac{p_{I1}m_2 x}{2p_{I2}\Omega_2\eta} d_{B2}^{\alpha} \right) x^{\frac{N_{I1}+m_2-3}{2}} \\ &\times \mathrm{W}_{\frac{1-N_{I1}-m_2-2N_{I2}+2q}{2}, \frac{N_{I1}-m_2}{2}} \left(\frac{p_{I1}m_2 x}{p_{I2}\Omega_2\eta} d_{B2}^{\alpha} \right) dx. \end{aligned} \quad (20)$$

Finally, one can derive the CDF of γ_2 as (6) by using [15].

REFERENCES

[1] S. Sudevalayam, P. Kulkarni, "Energy harvesting sensor nodes: Survey and implications," *IEEE Commun. Surv. Tutorials*, vol. 13, no. 3 pp. 443-461, Third Quarter 2011.

[2] G. Pan, C. Tang, T. Li, and Y. Chen, "Secrecy performance analysis for SIMO simultaneous wireless information and power transfer systems," *IEEE Trans. Commun.*, vol. 63, no. 9, pp. 3423-3433, Sept. 2015.

[3] G. Pan, H. Lei, Y. Deng, L. Fan, J. Yang, Y. Chen and Z. Ding, "On secrecy performance of MISO SWIPT systems with TAS and imperfect CSI," *IEEE Trans. Commun.*, vol. 64, no. 9, pp. 3831-3843, Sept. 2016.

[4] G. Pan, H. Lei, Y. Deng, L. Fan, J. Yang, Y. Chen and Z. Ding, "Performance analysis and optimization for SWIPT wireless sensor networks," to appear in *IEEE Trans. Commun.*, doi: 10.1109/TCOMM.2017.2676815.

[5] Z. Ding et al., "Application of smart antenna technologies in simultaneous wireless information and power transfer," *IEEE Commun. Mag.*, vol. 53, no. 4, pp. 86-93, April 2015.

[6] L. Liu, R. Zhang, and K.-C. Chua, "Wireless information transfer with opportunistic energy harvesting," *IEEE Trans. Wireless Commun.*, vol. 12, no. 1, pp. 288-300, Jan. 2013.

[7] Y. Chen, "Energy harvesting AF relaying in the presence of interference and Nakagami-m fading," *IEEE Trans. Wireless Commun.*, vol. 15, no. 2, pp. 1008-1017, Feb. 2016.

[8] S. Kim , Y. Ko , H. Heo "Outage analysis of amplify-and-forward partial relay selection scheme with multiple interferers," *IEEE Commun. Lett.*, vol. 15, no. 12, pp. 1281-1283, Dec. 2011.

[9] I. Krikidis, J. Thompson, S. McLaughlin, *et al.* "Amplity-and-forward with partial relay selection," *IEEE Commun. Lett.*, vol. 12, no. 4, pp. 235-237, Apr, 2008.

[10] G. Pan, Y. Chen and Q. Feng, "Performance analysis of interference-limited cooperative systems with relay selection over independent log-normal fading channels," *IET Commun.*, vol. 8, no. 10, pp. 1751-1761, July 2014.

[11] Y. Zhou, G. Pan, T. Li, H. Liu, C. Tang and Y. Chen, "Secrecy outage performance for partial relay selection schemes in cooperative systems," *IET Commun.*, vol. 9, no. 16, pp. 1980-1987, Nov. 2015.

[12] A. Papoulis, S. U. Pillai, *Probability, Random Variables and Stochastic Processes, Ed. 4th*, Academic Press, 2002.

[13] I.S. Gradshteyn, and I.M. Ryzhik, *Table of Integrals, Series, and Products 7th.*, Academic Press, 2007.

[14] A.P. Prudnikov, Yu.A. Brychkov, O.I. Marichev, *Integrals and Series, Vol.2 Special Functions*, New York: Gordon & Breach Sci. Publ., 1986.

[15] http://functions.wolfram.com/07.45.21.0004.01.