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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.

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 (\(\gamma_0\)), D sends a request to the relay asking it to forward the decoded 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

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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

$$y_{sr} = \sqrt{P_s d_{B1}^3} h_{sr}s + \sum_{j=1}^{N_1} \sqrt{Q_j d_{ir,j}^3} g_j s_j + n_{ra} + n_{rc},$$

$$y_{sd} = \sqrt{P_s d_{B3}^3} h_{sd}s + \sum_{j=1}^{N_3} \sqrt{Q_j d_{ij,j}^3} g_j s_j + n_{da} + n_{dc},$$

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, $d_{ij,j}$ ($j \in \{1, 2, \cdots, N_3\}$) is the distance between the j-th interferer and D in the 1st phase, $\alpha$ 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 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 $\sigma_{ra}^2$ and $\sigma_{rc}^2$. $Q_j$ and $Q_3$ 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 $|h_{ij}|^2$ and $|g_{ij}|^2$, $i = 1, 2, 3, j = 1, 2, \cdots, N$, follow Gamma distributions with probability density functions (PDFs), $f_{|h_{ij}|^2}(x) = \left(\frac{m_i}{\bar{h}_{ij}}\right)^{m_i-1} x^{m_i-1} e^{-\frac{m_i x}{\bar{h}_{ij}}}$, $f_{|g_{ij}|^2}(x) = \left(\frac{m_j}{\bar{g}_{ij}}\right)^{m_j-1} x^{m_j-1} e^{-\frac{m_j x}{\bar{g}_{ij}}}$, respectively, where $m_i$ and $\bar{h}_{ij}$ are the parameter and the average fading power in the S-R link, and $m_j$ and $\bar{g}_{ij}$ are the parameter and the fading power in the link from the j-th interferer to the relay.

Define $\gamma_{sr_d} = \gamma_{s2r_d} = \gamma_{sr_d}$, $k = 1, 2, \cdots, N$. Therefore, the SINR of the received signal at R and D can be written as

$$\gamma_1 = \frac{P_s d_{B1}^3 \sum_{j=1}^{N_1} Q_j d_{ir,j}^3 |g_j|^2 + \sigma_{ra}^2 + \sigma_{rc}^2}{P_s d_{B1}^3 \sum_{j=1}^{N_3} Q_j d_{ir,j}^3 |g_j|^2 + \sigma_{ra}^2 + \sigma_{rc}^2},$$

and

$$\gamma_3 = \frac{P_s d_{B3}^3 \sum_{j=1}^{N_3} Q_j d_{ij,j}^3 |g_j|^2 + \sigma_{da}^2 + \sigma_{dc}^2}{P_s d_{B3}^3 \sum_{j=1}^{N_1} Q_j d_{ij,j}^3 |g_j|^2 + \sigma_{da}^2 + \sigma_{dc}^2},$$

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 $Y_2 = \sum_{j=1}^{N_2} Q_j d_j^{-\alpha_j} |g_j|^2$, $n_3 = \sigma_{d3}^2 + \sigma_{a3}^2$. Similarly, the PDF of $Y_2$ can be derived by equation (17), (27).

The PDF of $P_r$ can be written as $f_{P_r}(x) = \frac{1}{P_1} \exp\left(\frac{-x}{\sqrt{\frac{N_3-N_2}{P_1}}}\right)$.

Then, the PDF and CDF of $\gamma_2$ can be presented as (5) and (6), respectively, as shown on the top of next page, where $C_2 = \frac{P_1 m_2 + \theta d_2 a_2}{\sum_{j=1}^{N_r} m_j^2 + \sum_{j=1}^{N_r} m_j^2 + \frac{1}{\gamma}}. \quad W_{a,b}(x)$ is the Whittaker Function, $\Gamma\left(\frac{a}{b}\right) = \frac{\Gamma(a)}{\Gamma(b)}$, $\Gamma_{m,n}(a, b_1, \ldots, b_q)$ is the Meijer Function, $\lambda$ is as shown on the top of next page. The derivations of the PDF and CDF of $\gamma_2$ can be found in Appendix.

B. Outage probability of OSRL scheme

The output SINR of the combiner can expressed as $\gamma_D = \begin{cases} \gamma_3, & \gamma_3 > \gamma_0 \\ \max\{\gamma_{eq}, \gamma_3\}, & \gamma_3 \leq \gamma_0 \end{cases}$, 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 $\gamma_{sr}$ and $\gamma_{eq}$ can expressed as $F_{\gamma_{sr}}(\gamma_{sr}) = \left[F_{\gamma_{srk}}(\gamma_{srk})\right]^{N_r}$ and $F_{\gamma_{eq}}(\gamma_{eq}) = F_{\gamma_{sr}}(\gamma_{eq}) + F_{\gamma_{eq}}(\gamma_{eq}) - F_{\gamma_{sr}}(\gamma_{eq})$.

Thus, the OP for OSRL scheme can be expressed as

$$P_{out}(\gamma_d < \gamma_{th}) = P\{\gamma_3 \leq \gamma_0\} P\{\max\{\gamma_{eq}, \gamma_3\} \leq \gamma_{th}\}$$

$$+ P\{\gamma_3 > \gamma_0\} P\{\gamma_3 > \gamma_{th}\}$$

$$= P\{\gamma_{eq} \leq \gamma_{th}\} \min\{\gamma_{th}, \gamma_0\}$$

$$+ P\{\gamma_0 < \gamma_3 \leq \gamma_{th}\}. \quad (8)$$

where $\gamma_{th}$ is the threshold SINR for outage events.

Finally, we can derived the OP for OSRL as

$$P_{out}(\gamma_d < \gamma_{th})$$

$$= \begin{cases} F_{\gamma_{eq}}(\gamma_{th}) F_{\gamma_3}(\min\{\gamma_{th}, \gamma_0\}) & \gamma_{th} > \gamma_0 \\ F_{\gamma_3}(\gamma_{th}) F_{\gamma_3}(\min\{\gamma_{th}, \gamma_0\}) & \gamma_{th} \leq \gamma_0 \end{cases} \quad (9)$$

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 $F_{\gamma_{eq}}(x) = \left[F_{\gamma_1}(x) + F_{\gamma_2}(x) - F_{\gamma_1}(x) F_{\gamma_2}(x)\right]^{N_r}$.

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

IV. NUMERICAL RESULTS AND DISCUSSIONS

For simplification, in this section we use $\Omega_1$, $\Omega_2$, $\Omega_3$, $\Omega_1$, $\Omega_1$, $m_1, m_2, m_3$, $m_1$, $m_2$, $m_3$, $m_1$ and $m_2$ to denote $\Omega_{srk}$, $\Omega_{rkd}$, $\Omega_{sd}$, $\Omega_{jr}$, $\Omega_{jd}$, $m_{srk}$, $m_{rkd}$, $m_{sd}$, $m_{jr}$ 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, $m_1 = m_2 = m_3 = 2$ dB, $\Omega_1 = 1$ dB, $\Omega_2 = 10$ dB, $\Omega_3 = 1$ dB, $Q_D = 0.8$ dB, $\Omega_{l1} = \Omega_{l2} = \Omega_{l3} = 2$ 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 $\eta = 0.4$.

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 $(N_1, N_2, N_3)$. 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
\[ f_{\gamma_2}(\gamma_2) = \lambda \times d^{\alpha}_{B2} \exp \left( \frac{p_{11}m_2 \gamma_2}{2p_{12} \Omega_2 \eta} d^{\beta}_{B2} \right) \left( d^{\gamma}_{B2} \right)^{-N_{12}+m_2-3} \left( \frac{N_{12}}{\Omega_1} \right)^{-\frac{N_{12}}{2}+\frac{N_{12}}{2}+\frac{N_{12}}{2}} \]  

(5)

\[ F_{\gamma_2}(\gamma_2) = \lambda \times C_2 \times G_{2,2}^{2,2} \left[ \frac{p_{11}m_2}{\eta \Omega_2} d^{\alpha}_{B2} \gamma_2 \right] \left( \frac{\eta m_2}{p_{11} \Omega_2} \right)^{N_{12}-m_2} \sum_{q=0}^{N_{12}-1} \left( \frac{N_{12} - 1}{q} \right) (-n_3)^q \Gamma(N_{11} + N_{12} - q) \Gamma(N_{12} - q + m_2) \]  

(6)

\[ \lambda = \frac{p_{12}}{\sqrt{\frac{m_2 \pi \Omega_2}{\eta}}} \Gamma(m_2) \Gamma(N_{11}) \eta \Gamma(N_{12}) \right) = \left( \frac{m_2 \pi \Omega_2}{\eta} \right)^{N_{12}-m_2} \sum_{q=0}^{N_{12}-1} \left( \frac{N_{12} - 1}{q} \right) (-n_3)^q \Gamma(N_{11} + N_{12} - q) \Gamma(N_{12} - q + m_2) \]  

(7)

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 \(x_1 = P_1 |h_1|^2\), \(y_1 = Y_1 - n_r\). Then, \(\gamma_1\) can be expressed as \(\gamma_1 = \frac{x_1}{y_1}\). Using (3), (9), and ([12], 6.60), we can derived the PDF as

\[ f_{\gamma_1}(\gamma_1) = d^{\alpha}_{B1} \int_0^\infty y_1 f_{x_1}(y_1) d^{\alpha}_{B1} \gamma_1 f_{y_1}(y_1) dy_1 \]

\[ = B_1 \times (d^{\alpha}_{B1} \gamma_1)^{m_1-1} \int_0^\infty y_1^{m_1} (y_1 - n_r)^{N_{11} - 1} \]

\[ \times \exp \left( -p_{11} (y_1 - n_r) - \frac{m_1 \gamma_1}{\Omega_1 P_1} d^{\alpha}_{B1} y_1 \right) dy_1. \]

(10)

where \((y_1 - n_r)^{N_{11}-1}\) can be written as

\[ (y_1 - n_r)^{N_{11}-1} = \sum_{r=0}^{N_{11}-1} \binom{N_{11}-1}{r} y_1^{N_{11}-1-r} (-n_r)^r. \]

(11)

Using (28) in (27), we can derive \(f_{\gamma_1}\) as

\[ f_{\gamma_1}(\gamma_1) = d^{m_1 \alpha}_{B1} B_1 \times \gamma_1^{m_1-1} \sum_{r=0}^{N_{11}-1} \binom{N_{11}-1}{r} (-n_r)^r \]

\[ \times \int_0^\infty y_1^{N_{11}-1-r+m_1} \exp \left( -p_{11} + \frac{m_1 d^{\alpha}_{B1} y_1}{\Omega_1 P_1} \right) y_1 dy_1. \]

(12)

relays representing a higher diversity gain.
Using ([13], 3.351.4), \( f_{\gamma_1} \) can be further rewritten as
\[
f_{\gamma_1}(\gamma_1) = d_{B_1}^{m_1} N_1 - 1 \sum_{r=0}^{N_1-1} \binom{N_1-1}{r} (-n_r)^r \times \left( \frac{d_{B_1}^{m_1} \gamma_1 + 1}{\Omega_1 P_s} \right) \times \sum_{r=0}^{N_1-1} \binom{N_1-1}{r} (p_{l1} - 1 - r + m_1)!. 
\]
(13)

B. Derivation of (5) and (6)

Define \( x_2 = P_r |h_2|^2 \), \( Y_2 = \sum_{i=3}^{N_2} Q_{i2} d_{t2}^m |y_2|^2, \) \( y_2 = Y_2 - n_3, \) \( P_r = \eta Y_1 \), the PDF of \( x_2 \) can be expressed as
\[
f_{x_2}(x_2) = \int_0^\infty \frac{1}{P_r} f_{|h_2|^2} (x_2) f_{P_r}(P_r) dP_r 
= \frac{x_2^{m_2-1} \left( \frac{m_2}{\Omega_2} \right)^2}{\Gamma(m_2) \Gamma(N_1)} \left( \frac{\eta m_2}{\eta} \right)^{N_1-m_2} P_{l1}^{N_1-m_2} \times \Gamma(N_1-1-m_2) \left( \frac{\eta m_2}{\eta} \right)^{N_1-m_2} \left( \frac{P_{l1}}{\Omega_2} \right)^{N_1-m_2} \times \int_0^\infty \left( -\frac{P_{l1}}{\eta} P_r - \frac{m_2 x_2}{\Omega_2 P_{l1}} \right) dP_r. 
\]
(16)

Using (13), 3.471.9, \( f_{x_2}(x_2) \) can be further written as
\[
f_{x_2}(x_2) = \frac{2}{\Gamma(m_2) \Gamma(N_1)} \left( \frac{\eta m_2}{\eta} \right)^{N_1-m_2} P_{l1}^{N_1-m_2} \times K_{N_1-m_2} \left( 2 \frac{P_{l1} m_2}{\Omega_2 p_{l1}} \right)^{N_1-m_2-1}. 
\]
(17)

Using (12), 6.60), the PDF of \( \gamma_2 \) can be derived as
\[
f_{\gamma_2}(\gamma_2) = d_{B_2}^{m_2} \gamma_2 \frac{N_2^{N_2-m_2}}{\gamma_2^{N_2-m_2}} \sum_{q=0}^{N_2-1} \sum_{q=0}^{N_2-1} \left( N_2 - 1 \right) \gamma_2^q \times (-n_3)^q \int_0^\infty K_{N_1-m_2} \left( 2 \sqrt{\frac{P_{l1} m_2}{\eta \Omega_2}} y_2 \right)^{N_1-m_2+2} e^{-\frac{P_{l1} y_2}{\eta \Omega_2}} dy_2, 
\]
(18)

where \( E_2 = \left( \frac{m_2}{\eta} \right)^{N_1} \Gamma(N_1) \Gamma(N_2) \Gamma(N_2) P_{l2} \left( \frac{m_2}{\eta} \right)^{N_1-m_2} \times W_{N_1-m_2} \left( \frac{P_{l1} m_2}{\eta \Omega_2} \right)^{N_1-m_2} \times \gamma_2. \)

Similarly, the CDF of \( \gamma_2 \) can be derived as
\[
F_{\gamma_2}(x) = \int_0^x f_{\gamma_2}(x) dx 
= \frac{2}{\Gamma(m_2) \Gamma(N_1)} \left( \frac{\eta m_2}{\eta} \right)^{N_1-m_2} P_{l1}^{N_1-m_2} \times \int_0^x \left( -\frac{P_{l1}}{\eta} P_r - \frac{m_2 x_2}{\Omega_2 P_{l1}} \right) dP_r. 
\]
(19)

Finally, one can derive the CDF of \( \gamma_2 \) as (6) by using [15].

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