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A tractable approach to analyzing the energy-aware two-way relaying networks in the presence of co-channel interference

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Abstract

Under the impact of co-channel interference (CCI) at two source nodes and the relay, we investigate the performance of dual-hop amplify-and-forward (AF) relaying networks. In terms of energy harvesting, the power-constrained relay first scavenges energy from the received signal and CCI signals then amplifies them and forwards them to the destination. In particular, we provide closed-form expressions for outage probability and bit error ratio (BER) to easily analyse the system performance. In this paper, the impact of distinct interference power level and the number of CCIs are derived. Monte Carlo simulations are used to provide expressions related to outage probability performance. It is confirmed that energy efficiency at the relay can be enhanced due to several advantages of CCI signals which can also prolong the life expectancy of relaying systems.

Keywords: Amplify-and-forward (AF), Co-channel interference (CCI), Bit error ratio (BER), Energy harvesting, Time switching, Two-way relaying

1 Introduction

Limited lifespan is a big problem of energy-constrained wireless communication networks. As a result, in order to ensure network connectivity, batteries need to be recharged or replaced periodically. Nevertheless, due to its high expenses, instability and complexity, harvesting energy from natural sources such as wind, solar or vibration which helps lengthen the lifetime of wireless communication networks has attracted much research interest. However, energy harvested from those sources depends on several factors, including weather conditions, which result in high requirements for reliable communication systems. Such limitations can be alleviated by harvesting energy from man-made radio frequency (RF) electromagnetic radiation [1, 2]. Wireless power transfer (WPT) through electromagnetic waves is a prime candidate in terms of energy harvesting (EH) techniques, which is easy to employ at the receiver compared to aforementioned sources. Recently, low-power electronic devices can be greatly supported thanks to the use of RF-EH

[3, 4]. Because both information and energy can be transmitted, simultaneous wireless information and power transfer (SWIPT) becomes increasingly popular with a huge number of research topics. The authors in [5, 6] investigated the balance between capacity and energy. In particular, some protocols, including time switching and power splitting for SWIPT systems, were given [7]. Furthermore, the optimal transmit co-variance and rate-energy region were obtained.

There have been a few works conducted on the performance of dual-hop cooperative networks under the impact of co-channel interference (CCI). The work in [8] focused on the end-to-end performance of multi-user amplify-and-forward (AF) cooperative networks and showed that CCI seriously impairs the relay-destination connection. In the case of average throughput, transmitting directly and over AF relaying systems by adjusting the number of interfering relays and the target signal-to-noise ratio (SNR) generates substantial gains. Regarding AF schemes, the impact of multi-user interference was carefully considered in case interference does not exist, in which according to asymptotic analysis, the diversity gain of the network is limited by interference [9]. The authors in [10] investigated opportunistic relaying under

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the impact of interference and thermal noise in case channel sensing is operated over slow fading environments. In [11], a dual-hop relay fading network was evaluated in terms of the performance of outage probability of AF and decode-and-forward (DF) relaying schemes in environments where less interference is expected, in which CCIs affect negatively the destination node when the relay node suffers from an additive white Gaussian noise (AWGN). Furthermore, the authors in [12] put forward an interference-aidede EH scheme for DF relaying networks, in which energy is harvested by the relay from the received signal and CCI signals; after that, the received information signal is decoded before being forwarded to the destination. In [13], the performance of multi-antenna two-way relay networks was considered, in which AF and DF relaying strategies wer systemically analysed, and they proposed an antenna selection scheme by optimizing the received SNR.

In principle, CCIs impair the performance of the system which are caused by some sources of interference. Regarding multi-hop relaying, a number of investigations on the impact of CCIs on the performance of the system were conducted. It is assumed that CCIs were subject to Rayleigh fading and the system performance which were evaluated in terms of outage probability, average symbol error probability (ASEP) and ergodic capacity [14, 15]. Meanwhile, CCIs were assumed to be subject to Nakagami-m fading channels to compute outage probability, error probability and ergodic capacity which were investigated in [16], and over Nakagami-m fading channels, the performance of CSI in AF multi-hop relaying networks under the impact of CCI was considered [17]. However, the performance metrics described above must be considered independently, if CCIs depend on Nakagami-m fading and solving mathematical problems is demanding. Furthermore, providing better practical insights into a tractable technique to investigate the system performance is nearly impossible as per the results in [16–18]. Furthermore, in [19], the authors focused on AF relaying networks based on two protocols: (i) time switching-based relaying (TSR) and (ii) power splitting-based relaying (PSR) for transmitting information and energy from source node to relay node. Meanwhile, in [20], the ergodic achievable secrecy rate (EASR) of multiple-antenna amplify-and-forward relaying networks was investigated, in which the relay can be wiretapped by an eavesdropper.

Unfortunately, in the presence of CCI, the EH relaying mode has not been comprehensively studied so we change the EH-assisted relay model in [19] to a two-way relay architecture and the impact of CCI is investigated. Moreover, the impact of CCI on every node in two-way relaying channels leads to the introduction of the fixed time switching regime in the EH protocol which has not been considered before. Regarding harvesting energy from both sources and CCI signals, we consider an AF relaying network which assists the power-constrained relay in transmitting signals to the destination. The contributions of our paper are described follows.

- We propose an EH protocol which can harvest energy with pre-calculated time switching coefficients from the source signals in two-way relaying networks and CCI to enhance transmission between the S_1 and S_2 source pair considering a dual-hop AF relaying network.
- Closed-form expressions for outage probability and throughput are provided for analysing the system performance. In fact, a tractable model for evaluating EH two-way relaying networks is first introduced under the impact of CCI, and hence, such a model is important to satisfy the acceptable QoS threshold for specific system performance.
- For tractable computation, we derive expressions of bit error ratio (BER) in both cases (with CCI and without CCI). These results can be checked easily by popular tools such as Matlab or Mathematica.
- We give numerical results to prove the impact of source power, interference power and the number of CCIs on the performance of outage probability and throughput. Meanwhile, controlling CCIs at acceptable limits can retain the quality of the transmission link, despite using power-constrained relays.

We organized this paper as follows: In Section 2, we introduce the system model and the proposed EH protocol. Expressions for outage probability and throughput of the system are provided, and the closed-form expression of BER is presented in Section 3. In Section 4, numerical results are given to prove analytical expressions. Eventually, Section 5 draws a conclusion for the paper.

Notation: $f_W(.)$ and $F_W(.)$ stand for the probability density function (PDF) and cumulative distribution function (CDF) of the random variable (RV) W, respectively. $\Pr\{.\}$ denotes the probability distribution. Statistical mean operation is denoted by $E[.]$.

2 System model

In Fig. 1, under the impact of CCI, we illustrate an EH relay-aided cooperative network, where a relay node R communicates with two sources S_1 or S_2. Information can be processed by the two source nodes in two time slots, in which in the first time slot, signals are transmitted to the relay at the same time by both sources S_1 and S_2 while during the next time slot, the received signal is amplified and then forwarded by the relay and both source nodes can receive the transmitted signal.

Fig. 1 System model
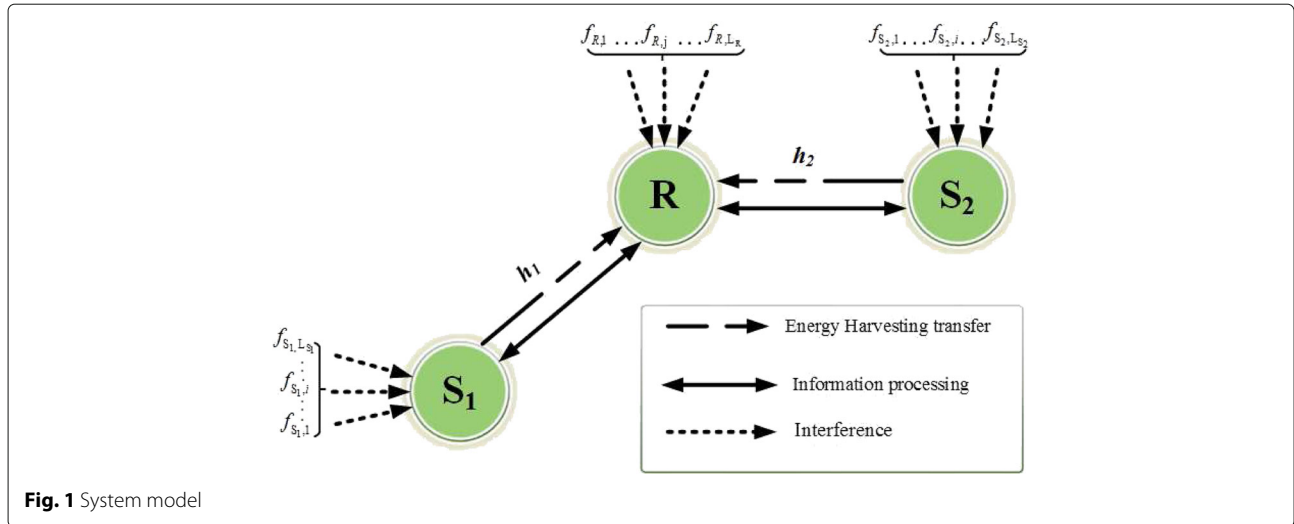
It is assumed that interference is not only considered as energy in EH but also noise in information processing. In two-way relaying networks, data flow is assumed to be between source nodes S_1 and S_2 in bidirectional transmission. Both nodes S_1 and S_2 are powered by a regulated power supply source E_S while energy can be harvested by the energy harvesting-assisted relay node by using wireless power based on the energy harvesting protocol. In this model, the received signal and CCI signals are considered as a new source of power for recharging the relay. Additionally, it is noted that each node is equipped with an antenna to increase spatial diversity.

The channel is assumed as block fading, in which the channel remains constant during the transmission of one block and varies from one block to another. In a signal block, $x_{S_k}(n)$ denotes the narrow-band transmit signal at S_k, $k \in \{1, 2\}$ with mean value expressed as $E\left[\left|x_{S_k}(n)\right|^2\right] = 1$, where time index is denoted by n and $d_{R,j}$ denotes as interferer signals, jth, to the relay node with unit mean value. Rayleigh fading channel is at each hop, and h_1 stands for channel gains between the source S_1 and the relay node, while h_2 represents as channel gains between the source S_2 and the relay node. The channel fading gain between the interferer ith and source S_1; S_2 is denoted as $f_{S_1,i}, f_{S_2,i}$ while the channel fading gain between the interferer jth and the relay node is $f_{R,j}$, in which $i = 1, \ldots, L_S, j = 1, \ldots, L_R$. For simplicity, it is noted that $L_{S_1} = L_{S_2} = L_S$. Besides that, E_S denotes as the transmitted power from the source, and it is equal to the transmit power allocation at two sources. Likewise, equal interference power allocation of various CCIs is denoted by E_I. Note that the number of CCIs at the relay is denoted by L_R while L_{S_1} stands for the number of CCIs at the source S_1, and L_{S_2} is the CCIs at the source S_2.

In fact, there is no data transmitted from S_1 to S_2 directly, and time slots are used by the two-hop link with the relay node $S_1 \rightleftarrows S_2$. Hence, the baseband-equivalent discrete time model for the received signal at the relay can be written as

$$y_R = \sqrt{E_S}h_1 x_{S_1} + \sqrt{E_S}h_2 x_{S_2} + \sqrt{E_I}\sum_{j=1}^{L_R} f_{R,j} d_{R,j} + n_R, \quad (1)$$

in which n_R denotes the AWGN components arriving at R, with $CN(0, N_0)$. For relay-aided link $S_1 \rightleftarrows R \rightleftarrows S_2$, the amplify-and-forward relay scheme is selected to be employed.

2.1 Energy harvesting

Instead of finding some ideal transmission strategies, we consider some relay strategies. In this paper, we carefully evaluate the outage probability of two-hop relaying networks under the impact of CCI and the energy harvesting-assisted relaying channel, in which the benefits of energy harvesting relay-aided cooperative transmission are verified. Furthermore, time switching- and AF-based relaying protocols are put forward.

In Fig. 2, the time switching-based relaying (TSR) protocol [19] includes two phases, energy harvesting and information processing. In the first phase, the harvested energy E_h processed in αT (in which α is the time switching fraction and T is the block time) is expressed by

$$E_h = \eta \alpha T \left(E_S|h_1|^2 + E_S|h_2|^2 + E_I \sum_{j=1}^{L_R} |f_{R,j}|^2 \right), \quad (2)$$

where $0 < \eta < 1$, which denotes as the energy harvesting conversion coefficient, relying on rectification circuitry. The transmitted power from the relay node E_R using

Fig. 2 TSR protocol for energy harvesting
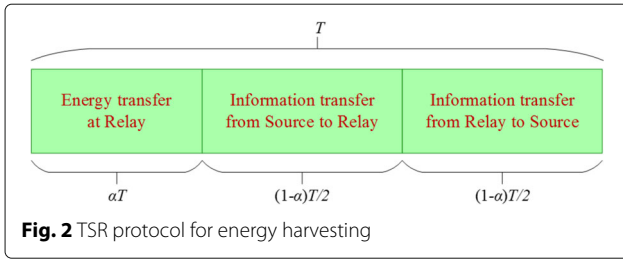
the TSR protocol proposed in [19] can be computed as follows:

$$E_R = \frac{E_h}{(1-\alpha)\,T/2} = \rho\left(E_S|h_1|^2 + E_S|h_2|^2 + E_I\sum_{j=1}^{L_R}\left|f_{R,j}\right|^2\right),$$
(3)

where $\rho = \frac{2\eta\alpha}{1-\alpha}$.

In the case of fixed harvesting power at relay, E_R, time switching coefficients can be calculated as

$$\alpha_0 = \frac{E_R}{2\eta\left(E_S\,|h_1|^2 + E_S\,|h_2|^2 + E_I\sum_{j=1}^{L_R}\left|f_{R,j}\right|^2\right) + E_R}.$$
(4)

As mentioned above, the relay-aided transmission can enhance the amount of power used to transmit signals at the relay. However, the value of instantaneous harvested power flow is time varying, due to the variation of sources of energy. Hence, the power output flow is not as stable as an ordinary power supply. In some cases, there is not enough energy for R. Therefore, the minimum amount of energy needed at each relay node to re-transmit signals is the pre-set power level and energy harvested from surrounding sources during a block time.

In principle, the constraint for fixed harvested power using TSR protocol in one-way relaying networks in the case of non-CCI can be expressed as

$$\frac{\eta\alpha_T E_S\,|h_1|^2}{(1-\alpha_T)/2} \le E_S,$$
(5)

where time switching fraction is denoted by α_T in one-way relaying networks [19].

Next, this equation is equivalent with

$$\rho E_S\,|h_1|^2 \le E_S.$$
(6)

In this paper, it is noted that under the impact of CCI, the constraint of the energy harvesting policy can be given as

$$\rho P_S|h_k|^2 \underset{k\in\{1,2\}}{=} \frac{P_I\sum_{i=1}^{L_{S_k}}\left|f_{S_k,i}\right|^2 + 1}{P_I\sum_{j=1}^{L_R}\left|f_{R,j}\right|^2 + 1}P_S,$$
(7)

where we denote $P_S = E_S/N_0$, $P_I = E_I/N_0$.

It is worth noting that CCI at the relay can contribute to the improvement of the energy harvesting power level at the relay in two-way relaying networks compared with one-way relaying networks. In (7), if the CCI term of $P_I\sum_{i=1}^{L_{S_k}}\left|f_{S_k,i}\right|^2$ is greater than $P_I\sum_{j=1}^{L_R}\left|f_{R,j}\right|^2$, the harvested power at the relay can be enhanced compared to the one-way relay regime.

Thus, the fixed time switching coefficient for the proposed energy harvesting protocol in this paper can be re-computed as

$$\alpha_1 = \frac{P_I\sum_{i=1}^{L_{S_k}}\left|f_{S_k,i}\right|^2 + 1}{2\eta\left(P_I\sum_{j=1}^{L_R}\left|f_{R,j}\right|^2 + 1\right)|h_k|^2 + P_I\sum_{i=1}^{L_{S_k}}\left|f_{S_k,i}\right|^2 + 1}.$$
(8)

Remark 1 *In this proposed energy harvesting protocol, the channel gains are significant due to exact channel estimation algorithms. For example, the perfect channel state information (CSI) is computed. As a result, the fixed time switching coefficient can be pre-calculated in the energy harvesting phase. However, such coefficient depends on CCIs and the channel gains. A feedback stream is required from relay to source to help the source find the fixed time switching coefficient properly. Note that α_1 belongs to $[0,1]$.*

3 Performance analysis
3.1 Signal-to-interference-plus-noise ratio analysis
In this two-way relaying model, R amplifies the received signal y_R with a gain G which is expressed as

$$G^2 = \left(E_S|h_1|^2 + E_S|h_2|^2 + E_I\sum_{j=1}^{L_R}\left|f_{R,j}\right|^2 + N_0\right)^{-1}.$$
(9)

This AF gain fraction in the high signal-to-interference-plus-noise ratio (SINR) regime can be expressed again as

$$G^2 \approx \left(E_S \left(|h_1|^2 + |h_2|^2 \right) + E_I \sum_{j=1}^{L_R} \left| f_{R,j} \right|^2 \right)^{-1}. \qquad (10)$$

In principle, the transmission of the current signal block at R is provided with enough energy before information is transferred from R to S_1 and S_2 in the broadcast phase; it must be sent from S_1 to S_2 first. In this paper, the AF-based two-way relaying protocol under the impact of CCI is evaluated in terms of energy harvesting capacity. The performance of SINR of S_1 is considered.

For simplicity, we only consider the outage performance at one source node, S_1, in which information is transmitted from R to S_1 in the broadcast phase, which is expressed as

$$y_{S_1} = Gh_1\sqrt{E_S}y_R + \sqrt{E_I}\sum_{i=1}^{L_{S_1}} f_{S_1,i}d_{S_1,i} + n_{S_1}, \qquad (11)$$

and

$$y_{S_2} = Gh_1\sqrt{E_S}y_R + \sqrt{E_I}\sum_{i=1}^{L_{S_2}} f_{S_2,i}d_{S_2,i} + n_{S_2}, \qquad (12)$$

where the AWGN components arriving at S_1 and S_2 are denoted by n_{S_1} and n_{S_2}, respectively, with mean value N_0 and $d_{S_k,i}$ denotes as interferer signals, ith, to the source S_k with unit mean value. It is noted that the average channel coefficients Ω_{h_1} and Ω_{h_2} are known at both sources S_1 and S_2 thanks to advanced channel estimation algorithms

$$y_{S_1} = Gh_1\sqrt{E_R}\left(\sqrt{E_S}h_1x_{S_1} + \sqrt{E_S}h_2x_{S_2} + \sqrt{E_I}\sum_{j=1}^{L_R} f_{R,j}d_{R,j} + n_R \right)$$
$$+ \sqrt{E_I}\sum_{i=1}^{L_{S_1}} f_{S_1,i}d_{S_1,i} + n_{S_1}, \qquad (13)$$

and

$$y_{S_2} = Gh_2\sqrt{E_R}\left(\sqrt{E_S}h_1x_{S_1} + \sqrt{E_S}h_2x_{S_2} + \sqrt{E_I}\sum_{j=1}^{L_R} f_{R,j}d_{R,j} + n_R \right)$$
$$+ \sqrt{E_I}\sum_{i=1}^{L_{S_2}} f_{S_2,i}d_{S_2,i} + n_{S_2}, \qquad (14)$$

when self-interference cancellation is adopted for the received signal of S_1 (i.e. their loop self-interference of

$Gh_1\sqrt{E_R}\sqrt{E_S}h_1x_{S_1}$ can be eliminated). For simplicity, the received signal at S_1 could be expressed as

$$y_{S_1} = Gh_1\sqrt{E_R}\sqrt{E_S}h_2x_{S_2} + Gh_1\sqrt{E_R}\sqrt{E_I}\sum_{j=1}^{L_R} f_{R,j}d_{R,j}$$
$$+ Gh_1\sqrt{E_R}n_R$$
$$+ \sqrt{E_I}\sum_{i=1}^{L_{S_1}} f_{S_1,i}d_{S_1,i} + n_{S_1} \qquad (15)$$

Thus, the end-to-end SINR $S_2 \to R \to S_1$ (it looks similar to the computation for SINR of the link $S_1 \to R \to S_2$) can be computed by

$$\gamma_{S_1} = \frac{G^2E_RE_S|h_1|^2|h_2|^2}{G^2|h_1|^2E_R\left(E_I\sum_{j=1}^{L_R} \left| f_{R,j} \right|^2 + N_0 \right) + E_I\sum_{i=1}^{L_{S_1}} \left| f_{S_1,i} \right|^2 + N_0}. \qquad (16)$$

We derive a new expression after simple manipulation which is given by

$$\gamma_{S_1} = \frac{\rho P_S|h_1|^2|h_2|^2}{\rho|h_1|^2\left(P_I\sum_{j=1}^{L_R} \left| f_{R,j} \right|^2 + 1 \right) + P_I\sum_{i=1}^{L_{S_1}} \left| f_{S_1,i} \right|^2 + 1}. \qquad (17)$$

It is not complicated to calculate all expressions in terms of SINR. Thus, it is important to achieve approximate expressions for outage probability of P_{out}, which can be expressed as follows:

$$\gamma_{S_1} = \frac{\dfrac{\rho P_S|h_1|^2}{P_I\sum_{j=1}^{L_R}\left| f_{R,j} \right|^2+1} \times \dfrac{P_S|h_2|^2}{P_I\sum_{i=1}^{L_{S_1}}\left| f_{S_1,i} \right|^2+1}}{\dfrac{\rho P_S|h_1|^2}{P_I\sum_{i=1}^{L_{S_1}}\left| f_{S_1,i} \right|^2+1}+\dfrac{P_S}{P_I\sum_{j=1}^{L_R}\left| f_{R,j} \right|^2+1}},$$
$$= \frac{X \times Y}{X + Y}|h_2|^2 \qquad (18)$$

where $X = \dfrac{\rho P_S|h_1|^2}{P_I\sum_{i=1}^{L_{S_1}}\left| f_{S_1,i} \right|^2+1}$ and $Y = \dfrac{P_S}{P_I\sum_{j=1}^{L_R}\left| f_{R,j} \right|^2+1}$.

3.2 Outage probability

Outage probability performance is considered in Lemma 1.

Lemma 1 X, Y *denote as arbitrary random variables with $X > 1$ and $Y > 1$. The tightness of the upper bound is determined as*

$$\frac{X \times Y}{X + Y} \le \min\left(X, Y \right). \qquad (19)$$

Proof We omit it here because it is widely used throughout the paper.

Nonetheless, in the case of $X = Y$, a new expression is given as

$$\frac{X \times Y}{X + Y} \le \min(X, Y) = X = Y. \tag{20}$$

Determining outage performance based on SINR at (18) is a problem. To the best of our knowledge, the closed-form expression of the outage probability in this case does not exist. It motivates us to find a tractable solution. Fortunately, if time switching in the proposed energy harvesting protocol is altered, we derive

$$\frac{\rho P_S |h_1|^2}{P_I \sum_{i=1}^{L_{S_1}} |f_{S_1,i}|^2 + 1} = \frac{P_S}{P_I \sum_{j=1}^{L_R} |f_{R,j}|^2 + 1}. \tag{21}$$

As a result, the upper bound of SINR at source S_1 is achieved

$$\gamma_{S_1,\text{up}} = \frac{P_S |h_1|^2}{P_I \sum_{j=1}^{L_R} |f_{R,j}|^2 + 1}. \tag{22}$$

As for the threshold rate, γ_{th}, the outage probability can be computed in an approximate manner as

$$
\begin{aligned}
P_{\text{out}}(\gamma_{\text{th}}) &\underset{k \in \{1,2\}}{=} F_{\gamma_{S_k},\text{up}}(\gamma_{\text{th}}) \\
&\underset{k \in \{1,2\}}{=} \Pr\left\{ \gamma_{S_k,\text{up}} \le 2^{2R_0} - 1 \overset{\triangle}{=} \gamma_{\text{th}} \right\},
\end{aligned} \tag{23}
$$

where the threshold rate is denoted by R_{S_0}.   □

Proposition 1 *In energy harvesting mode, the closed-form expression outage probability in an approximate manner at the source S_1 can be formulated as*

$$
\begin{aligned}
P_{\text{out}}(\gamma_{\text{th}}) &= \Pr(\gamma_{S_1,\text{up}} \le \gamma_{\text{th}}) \\
&= 1 - \left(\frac{P_S \Omega_{h_2}/P_I \Omega_f}{\gamma_{\text{th}} + P_S \Omega_{h_2}/P_I \Omega_f} \right)^{L_S} \exp\left(\frac{-\gamma_{\text{th}}}{P_S \Omega_{h_2}} \right).
\end{aligned} \tag{24}
$$

Proof See in the Appendix

Furthermore, in the case of no interference, i.e. when $L_S = 0$, the CDF of γ_{S_1} can be simplified as

$$P_{\text{out}}(\gamma_{\text{th}}) = 1 - \exp\left(\frac{-\gamma_{\text{th}}}{P_S \Omega_{h_2}} \right). \tag{25}$$

Interestingly, in high SNR, this assumption is equivalent with high transmit power at the source. Thus, the outage probability can be expressed when $P_{\text{out}}(\gamma_{\text{th}}) = 0$.   □

3.3 Throughput in delay-sensitive transmission mode

The instantaneous transmission rate is calculated as

$$R_i \underset{k \in \{1,2\}}{=} \log_2\left(1 + \gamma_{S_k,\text{up}} \right) \tag{26}$$

By contrast, by evaluating the outage probability, P_{out}, at a fixed source transmission rate, i.e. R_{S_0} (bits/s/Hz), throughput in the delay-sensitive mode is expressed as

$$\tau = (1 - \alpha) R_{S_0} (1 - P_{\text{out}}). \tag{27}$$

3.4 Bit error ratio

In this subsection, bit error ratio (BER) is considered, in which the error probability of several modulations can be determined by $E\left\{ pQ\left(\sqrt{2q\gamma} \right) \right\}$, where p and q represent modulation-specific constants, SINR is denoted by γ and $Q(.)$ denotes as error function.

The BER can be evaluated using a CDF-based approach which can be calculated as an integral of the CDF of SINR

$$\text{BER} = \frac{p\sqrt{q}}{2\sqrt{\pi}} \int_0^\infty \frac{e^{-qx}}{\sqrt{x}} F_{\gamma_{S_k},\text{up}}(x)\, dx, \tag{28}$$

where $F_{\gamma_{S_k},\text{up}}(x) = P_{\text{out}}(x)$. For example, BPSK modulation is investigated as following corresponding parameters $(p = q = 1)$.

Based on the expression of error derivation, a mathematical tractable form of BER in specific cases can be expressed by following propositions.

(i) Case 1: CCI

Let us first illustrate the key result as follows:

$$\left(\frac{1}{A\gamma + 1} \right)^{L_S} = \frac{A_1}{A\gamma + 1} + \frac{A_2}{(A\gamma + 1)^2} + \ldots + \frac{A_{L_S}}{(A\gamma + 1)^{L_S}}, \tag{29}$$

in which we denote $A = P_I \Omega_f / P_S \Omega_{h_2}$. It is confirmed that a partial fractions decomposition for $\left(\frac{1}{A\gamma + 1} \right)^{L_S}$ can be easily solved via finding $A_j, j = 1, \ldots, L_S$. Such parameters can be calculated since the fractions in the above equation have the same denominators, following that their numerators must be equal, and then we obtain A_j.

Proposition 2 *The exact form of BER can be expressed as follows:*

$$
\begin{aligned}
\text{BER}_1 &= p\sqrt{\frac{q}{\pi}} \int_0^\infty \frac{\exp(-q\gamma)}{\sqrt{\gamma}} d\gamma\, p\sqrt{\frac{q}{\pi}} \sum_{j=1}^{L_S} A_j \frac{\exp(-q\gamma)}{\sqrt{\gamma}} \\
&\quad \exp\left(\frac{-\gamma}{P_S \Omega_{h_2}} \right) (A\gamma + 1)^{-j} d\gamma,
\end{aligned} \tag{30}
$$

and the closed form of BER is

$$\text{BER}_1 = p - p\sqrt{\frac{q}{A}} \Psi\left(\frac{1}{2}; \frac{3}{2} - L_S; \frac{q + \frac{1}{P_S \Omega_{h_2}}}{A} \right), \tag{31}$$

where the function $\Psi(x; y; z)$ is the confluent hypergeometric function of the second kind, defined by the integral

$$\Psi(x; y; z) = \frac{1}{\Gamma(x)} \int_0^{\infty} e^{-zt} t^{x-1} (1+t)^{y-x-1} \, dt. \quad (32)$$

Proof The closed-form expression of BER in (30) results from substituting (29) into (24) and then applying the BER expression given in (28).

(ii) Case 2: Non-CCI

Interestingly, we henceforth consider the no co-channel interference regime (i.e. $L_S = 0$) and obtain the following results.

Regarding the ideal interference (CCI is approximately 0), we can derive a new expression of BER as follows: □

Proposition 3 *In the special case of non-CCI, the error probability can be significantly simplified to*

$$\text{BER}_2 = \frac{p}{2\sqrt{\pi}} \Phi\left(\frac{1}{2}, qc\right) - \frac{p\sqrt{q}}{2\sqrt{\pi}\sqrt{q + \frac{1}{P_S \Omega_{h2}}}} \\ \Phi\left(\frac{1}{2}, qc + \frac{c}{P_S \Omega_{h2}}\right), \quad (33)$$

where $\Phi(m, y) = \int_0^y t^{m-1} e^{-t} dt$ *is the lower incomplete gamma function and c is the threshold SNR.*

Proof The closed-form expression of BER in (33) follows from computing (28) using the outage probability in (25). □

4 Simulation results

In this section, the simulation results are presented to prove the theoretical examinations in terms of outage probability, the average BER and throughput. Note that there is a relay between S_1 and S_2, while d_1 and d_2 denote the distance between S_1 and R and S_2 and R, respectively. These distances are normalized as a unit, except in the last simulation as changing such distances satisfies $d_1 + d_2 = 2$. Consequently, h_1 and h_2 can be computed by $\Omega_{h_1} = d_1^{-\nu}$ and $\Omega_{h_2} = d_2^{-\nu}$, respectively, where ν represents the path loss exponent which is set to 4. It is assumed that all channels are flat Rayleigh fading channels, in which elements are independent identically distributed Gaussian random variables, in which the variance is 1 and the mean value is 0. Meanwhile, flat Rayleigh fading channel coefficients of the interference channels are $\Omega_{f_{R,j}} = \Omega_{f_{S_k,i}} = 0.7$. Besides that, the equation of power allocation between two terminals and one relay node is $E_{S_1}/N_0 = E_{S_2}/N_0 = E_S/N_0 = P_S$. Without loss of generality, it is assumed that $L_{S_1} = L_{S_2} = L_S$.

In Fig. 3, the number of interferers is altered and the approximate equal-power allocation interference case is considered, i.e. P_I is a constant value. We set parameters such as $P_I = P_S/20$ (dB), $\eta = 0.4$. This experiment illustrates that the approximate theory results and simulation match well with the accurate results even at a low P_S region. Thus, the closed-form approximate formulas provided in this paper are approximately similar to the accurate formulas, and system performance can be evaluated by using such formulas. It can be seen that when the number of interferers increases, the outage probability falls. Moreover, in Fig. 4, outage performance is examined in terms of different values of interference power. Note that if the interference power increases, the outage probability is near the outage limit.

Figure 5 depicts the impact of energy harvesting conversion efficiency on throughput, and numerical results are presented in two cases, interference free and CCI, and the AF outage performance. Interestingly, if the transmit power increases over a specific limit, e.g. $P_S = 30$ dB, outage performance also remains at both very low harvested power efficiency ($\eta = 0.1$) and medium harvested power efficiency ($\eta = 0.4$).

Figure 6 considers the average BER performance at source S_1 as a function of a different number of interferers. The BER performance in the case of no interference is evaluated. Furthermore, it is clear that the system performance falls dramatically during the power transmitting period. The performance gap between non-CCI and CCI is obvious.

In Fig. 7, the similar linear trend can be observed, in which the transmission rate is evaluated versus the transmit power of the source node. Note that the instantaneous transmission rate is affected by the interference power.
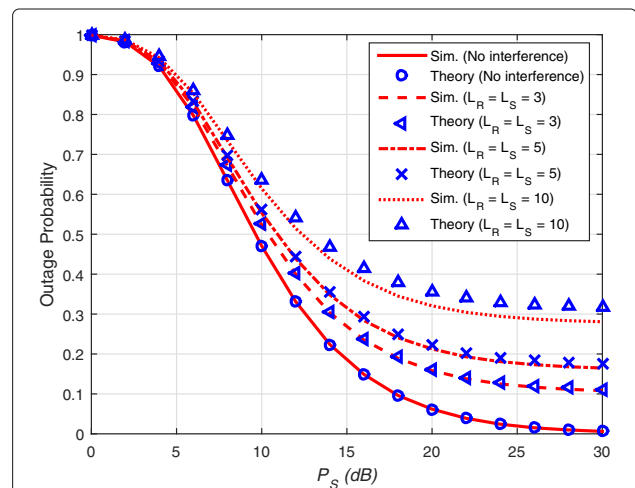

Fig. 3 Outage probability versus the transmit power of the source node with different values of interference power $P_I = P_S/20$ (dB), $\eta = 0.4$

Fig. 4 Outage probability versus the transmit power of the source node with different values of interference power with $L_S = L_R = 3$

Fig. 6 BER in two-way relaying networks for different values of the transmit power of the source node with $P_I = 5$ (dB)
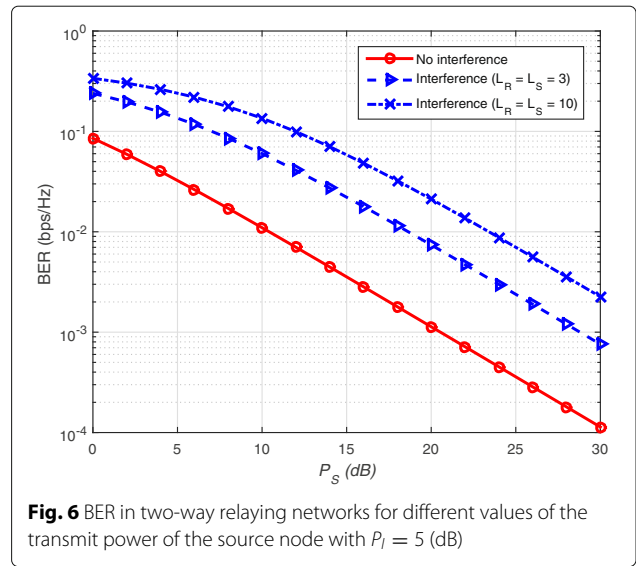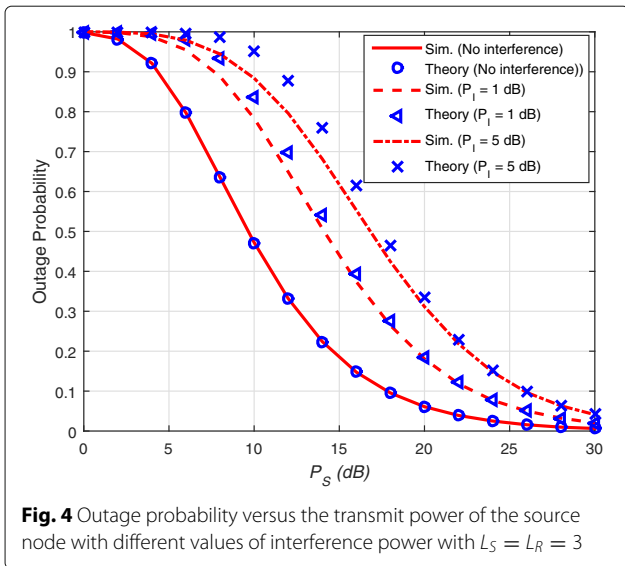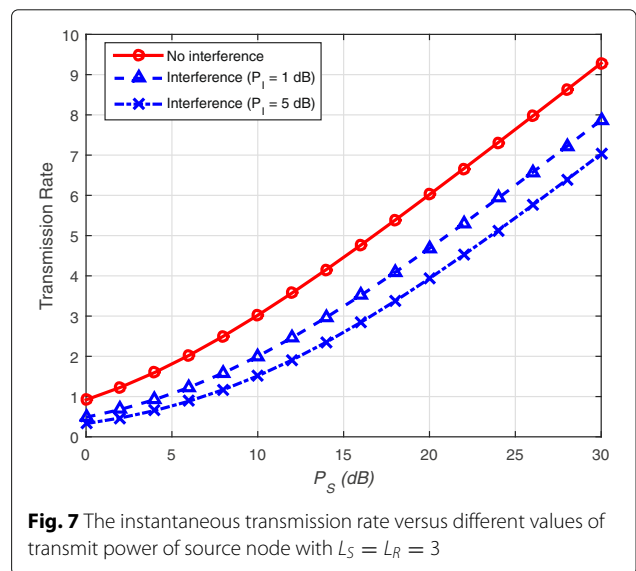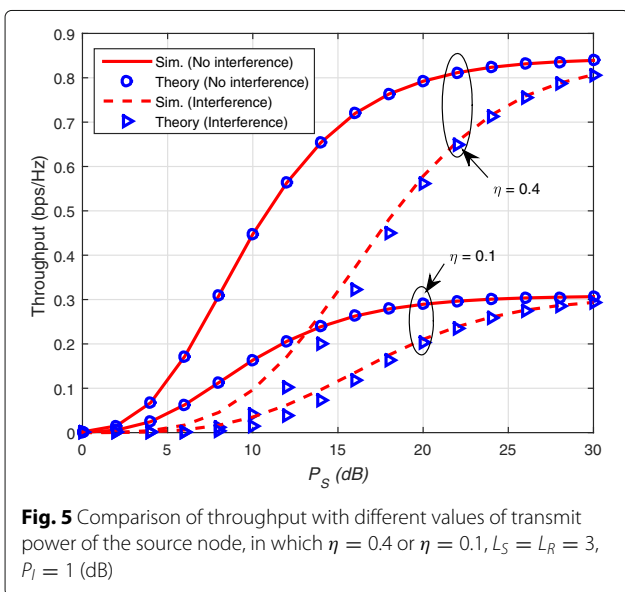
Figure 8 considers time allocation in the case of energy harvesting and information processing under non-CCI and CCI cases. Strikingly, the amount of time used for energy harvesting and information processing is equal in an interference-free case. Particularly, as interferer power is high, it increases the harvested energy and reduces time switching fraction.

In the next experiment, we evaluate the impact of physical distance between the source and the relay node on throughput performance as in Fig. 9. This illustration confirmed that the throughput is high when the relay node is closest to the source node. The optimal throughput can be obtained as approximately $d_1 = 0.7$ in the case of

CCI and as $d_1 = 0.4$ in the case of non-CCI. Similarly, controlling the interference power level plays an important role in maintaining the system throughput. However, the throughput suddenly changes much by increasing $d_1 = 0.8$ beyond 0.8. The reason is that the relay node experiences further distance compared with a wireless powered source, which results in fewer values of harvested energy for the remaining reliable communication between the relay and destination nodes. Interestingly, this result is totally different from the traditional case of a non-energy harvesting-assisted system, in which the maximum throughput is obtained when the position of the relay is between the source and the destination node.
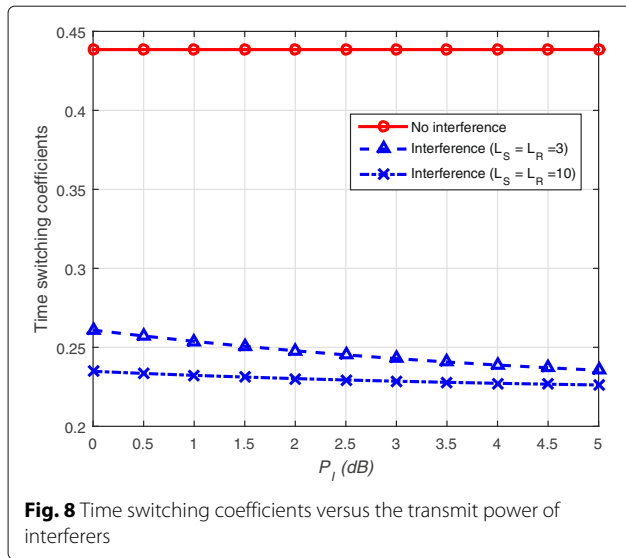

Fig. 5 Comparison of throughput with different values of transmit power of the source node, in which $\eta = 0.4$ or $\eta = 0.1$, $L_S = L_R = 3$, $P_I = 1$ (dB)

Fig. 7 The instantaneous transmission rate versus different values of transmit power of source node with $L_S = L_R = 3$

Fig. 8 Time switching coefficients versus the transmit power of interferers

5 Conclusions

In this paper, we have carefully analysed RF-based energy harvesting scheme for two-way relaying networks. In particular, the impact of CCI on the performance of AF-based two-way relaying networks is also evaluated for Rayleigh fading channels. When the number of CCIs is altered, we can achieve the exact expressions for SINR and approximate closed-form expressions for outage probability and throughput. Furthermore, to match well with the Monte Carlo simulations in different experiments, analytical expressions are provided. We investigate the impact of CCI and the transmit power of the source node in terms of outage probability and throughput performance to achieve the optimal trade-off. The result is the advantages of energy harvesting in the presence of CCI and
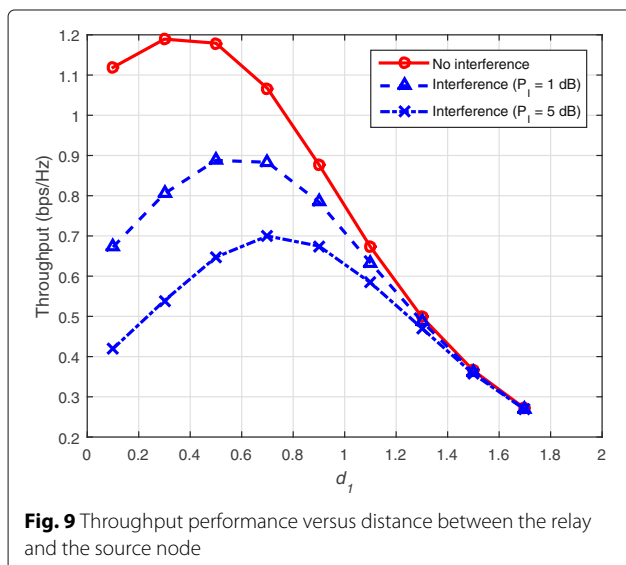

Fig. 9 Throughput performance versus distance between the relay and the source node

the parameters, e.g. the number of CCIs and the transmit power of the source which can optimize the throughput and BER performance. Moreover, the closed-form expression of BER in the two-way relaying model considering the presence of CCI is given.

Appendix

Proof of Proposition 1 We first rewrite SINR in the following form to obtain the CDF of the upper-bound SINR at node S_1

$$\gamma_{S_1,\text{up}} = P_S|h_1|^2 / (C_{S_1} + 1), \tag{34}$$

where $C_{S_1} = P_I \sum_{i=1}^{L_{S_1}} |f_{S_1,i}|^2$.

Next, the PDFs of $P_S|h_2|$ and C_{S_1} can be written, respectively, as

$$f_{P_S|h_2|}(x) = (1/P_S\Omega_{h_2}) \exp(-x/P_S\Omega_{h_2}), \tag{35}$$

and

$$f_{C_{S_1}}(x) = (1/P_I\Omega_f)^{L_{S_1}} \frac{x^{L_{S_1}-1}}{(L_{S_1}-1)!} \exp(-x/P_I\Omega_f). \tag{36}$$

Then, the CDF of SINR is obtained as [18, 21]

$$F_{\gamma_{S_1,\text{up}}}(\gamma) = 1 - \left(\frac{P_S\Omega_{h_1}/P_I\Omega_f}{\gamma + P_S\Omega_{h_1}/P_I\Omega_f}\right)^{L_{S_1}} \exp\left(\frac{-\gamma}{P_S\Omega_{h_1}}\right). \tag{37}$$

This ends the Proof of Proposition 1.　　□

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