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Secrecy outage performance for wireless-powered relaying systems with nonlinear energy harvesters*

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Abstract: We consider a cooperative system consisting of a source node, a destination node, N ($N > 1$) wireless-powered relays, and an eavesdropper. Each relay is assumed to be with a nonlinear energy harvester, in which there exists a saturation threshold, limiting the level of the harvested power. For decode-and-forward and power splitting protocols, the Kth best relay is selected to assist the source-relay-destination transmission. An analytical expression for the secrecy outage probability is derived, and also verified by simulation.

Key words: Decode-and-forward; Energy harvesting; Nonlinear; Secrecy outage probability
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1 Introduction

Recently, physical-layer (PHY) security in cooperative systems has attracted a lot of research interest, as it has the joint advantages of cooperative techniques and information-theoretic security by characterizing the physical channels in wireless communications. Wang and Xia (2015) presented a thorough overview of PHY security in cooperative systems. Three different types of diversity techniques including cooperative diversity were introduced to improve PHY security in Zou *et al.* (2015b). Zou *et al.* (2015a) first proposed single- and multi-relay selection schemes for a secondary system, and then derived the intercept probability as well as the outage probability (OP) in cognitive radio networks. By considering both amplify-and-forward (AF) and decode-and-forward (DF) protocols, a best relay was selected to improve PHY security in cooperative systems in Zou *et al.* (2013). Based on the network coding technique, Zhou *et al.* (2015) analyzed the secrecy performance in terms of the secrecy outage probability (SOP) in a cooperative network.

However, relays in cooperative systems need extra power to assist the transmissions (Chen, 2016). It is a serious problem for those relays powered by batteries due to the limited operational lifetime. To prolong the lifetime of relays, wireless-powered relaying (WPR) has been introduced. Energy harvesting from radio frequency (RF) is green and safe, and it is a new renewable energy resource for wireless power transfer as the energy is from either background signals or sources (Krikidis *et al.*, 2014; Ding *et al.*, 2015). Furthermore, it can overcome the limitations of some other renewable energy resources, such as solar, wind, and magnetic induction, which are used only in particular applications (Krikidis *et al.*, 2014; Ding *et al.*, 2015). Therefore, it is very interesting to consider the energy harvesting from RF. Taking into

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account the presence of interference both at the relay and at the destination, Chen (2016) investigated OP and the throughput for WPR with an AF protocol, in which both power splitting (PS) and time switching receivers were employed and compared. In Gu and Aïssa (2015), ergodic and outage capacities were studied for WPR. Ding *et al.* (2014b) studied two power allocation schemes, namely a non-cooperative scheme and an auction-based scheme, for WPR in a cooperative network. Zhang *et al.* (2016) derived the upper and lower bounds of probability of the strictly positive secrecy capacity for an underlay cognitive radio network with a full-duplex wireless-powered secondary system. Considering spatially random WPR, a stochastic geometry method was applied to obtain the OP and the diversity gain in Ding *et al.* (2014a). Taking into consideration a resource allocation algorithm, Ng *et al.* (2014) investigated the PHY security for a multiple-user multiple-input single-output system.

Note that all the aforementioned works about WPR are based on a linear energy harvester (EH) model. However, recent studies by Boshkovska *et al.* (2015) and Dong *et al.* (2016) showed that the linear EH model is not practical, because the electronic devices used in the power conversion circuits are nonlinear. It is interesting to consider the effect of a nonlinear EH mode on PHY secrecy performance. To the best of our knowledge, no such work has been reported in the literature.

In this study, we investigate PHY security for WPR with a nonlinear EH in cooperative systems. Specifically, a cooperative system consisting of a source node, a destination node, N ($N > 1$) WPR nodes, and an eavesdropper is considered. The PS method is implemented in the relays to simultaneously receive the information and to harvest energy from the source. Since a best relay may not always be selected because of the complex communication environments, the Kth best relay, leading to the Kth maximization for the secrecy capacity of the source-relay-destination link, is selected instead. In particular, an analytical expression for SOP is derived. Moreover, the new innovation points compared to Ng *et al.* (2014) are: (1) The non-linearity of the energy harvester is investigated, which has yet to be studied when considering PHY security; (2) The Kth best relay selection is taken into consideration.

2 System model

We consider a cooperative system, in which Alice transmits confidential information to Bob through N WPR nodes (R_n, $n \in \{1, 2, \ldots, N\}$) in the presence of an eavesdropper (Eve). For simplicity, each node in the system is assumed to be with a single antenna. For future work, multi-antenna technologies, i.e., antenna switching and spatial switching, can also be introduced into our considered system to improve system performance (Krikidis *et al.*, 2014). For example, we can assume the relays in our system to be equipped with multiple antennas. Under an antenna switching protocol, those multiple antennas can be divided into two groups, one for information decoding and the other for energy harvesting. With a generalized selection combining technique, those multiple antennas can be optimally assigned for information decoding and energy harvesting. The harvested energy from the assigned antennas can be combined and stored in a nonlinear EH, which can be used to forward the processed information in the second phase. Similarly, a spatial switching technique can be applied in our system when considering multiple antennas from the spatial domain (Krikidis *et al.*, 2014). We assume that WPR nodes have no external power supply, and only harvest energy from Alice for transmitting. DF and PS protocols are adopted in the receivers at WPR nodes. All WPR nodes are assumed to have the same PS factor ρ ($0 \leq \rho \leq 1$) and an energy conversion efficiency η ($0 \leq \eta \leq 1$). It is assumed that the direct Alice-Bob channel does not exist due to long distance and deep fading (Mo *et al.*, 2012; Chen, 2016). All channel state information is assumed to be known, and the Kth best relay is selected to assist the Alice-Bob transmission. We further assume that all the fading channels are independent and identically Rayleigh-distributed with channel coefficients h_{ij}, $i, j \in$ {Alice (S), Bob (D), Eve (E), R_n}. Hence, the channel gains, $|h_{ij}|^2$, are independently exponentially distributed with the probability density function (PDF) and cumulative distribution function (CDF), respectively denoted as

$$f_{|h_{ij}|^2}(x) = \frac{1}{g_{ij}} \exp\left(-\frac{x}{g_{ij}}\right), \tag{1}$$

$$F_{|h_{ij}|^2}(x) = 1 - \exp\left(-\frac{x}{g_{ij}}\right), \tag{2}$$

where g_{ij} is the expectation of the channel power gain (Proakis, 2000). To simplify the analysis, we assume that h_{SR_n}, $h_{\mathrm{R}_n\mathrm{D}}$, and $h_{\mathrm{R}_n\mathrm{E}}$ ($n \in \{1, 2, \ldots, N\}$) have the same expectations of channel power gains, being g_{SR}, g_{RD}, and g_{RE}, respectively.

The whole communication process is divided into two phases. In the first phase, Alice transmits information to all WPR nodes while Eve can wiretap the information. The Kth best relay, selected by Bob, simultaneously decodes the information and harvests energy. In the second phase, the selected relay broadcasts the processed information to Bob while Eve is overhearing the information.

In the first phase, the information signals received at the nth relay and Eve are

$$y_{\mathrm{R}_n} = \sqrt{1-\rho}\left(\sqrt{P_\mathrm{s}}h_{\mathrm{SR}_n}X_\mathrm{s} + n_{\mathrm{R}_n a}\right) + n_{\mathrm{R}_n c}, \quad (3)$$

$$y_{\mathrm{E}_1} = \sqrt{P_\mathrm{s}}h_{\mathrm{SE}}X_\mathrm{s} + n_\mathrm{E}, \quad (4)$$

respectively, where P_s denotes the transmitted power at Alice and X_s is the transmitted symbol at Alice. It is assumed that the additive white Gaussian noise (AWGN) $n_{\mathrm{R}_n a}$ and n_E are with zero mean and the same variance (N_0), and $n_{\mathrm{R}_n c}$ is the signal processing noise at R_n which is also assumed to be AWGN with zero mean and a variance of σ_n^2 (Pan *et al.*, 2015). Thus, the instantaneous signal-to-noise ratios (SNRs) at R_n and Eve are respectively

$$\gamma_{\mathrm{R}_n} = \frac{(1-\rho)P_\mathrm{s}|h_{\mathrm{SR}_n}|^2}{(1-\rho)N_0 + \sigma_n^2}, \quad \gamma_{\mathrm{E}_1} = \frac{P_\mathrm{s}|h_{\mathrm{SE}}|^2}{N_0}.$$

In the second phase, the selected relay (R_n) decodes the information and consumes the harvested energy to broadcast the processed information to Bob in the presence of Eve's eavesdropping. The received signals at Bob and Eve are

$$y_\mathrm{D} = \sqrt{P_{\mathrm{R}_n}}h_{\mathrm{R}_n\mathrm{D}}X_\mathrm{s} + n_\mathrm{D}, \quad (5)$$

$$y_{\mathrm{E}_2} = \sqrt{P_{\mathrm{R}_n}}h_{\mathrm{R}_n\mathrm{E}}X_\mathrm{s} + n_\mathrm{E}, \quad (6)$$

respectively, where n_D is the AWGN with zero mean and a variance of N_0, and P_{R_n} is the transmitted power at R_n, which is the EH from Alice in the first phase. Since a nonlinear EH is considered in this study, P_{R_n} can be expressed as (Dong *et al.*, 2016)

$$P_{\mathrm{R}_n} = \begin{cases} \rho\eta P_\mathrm{s}|h_{\mathrm{SR}_n}|^2, & P_\mathrm{s}|h_{\mathrm{SR}_n}|^2 \le \varGamma, \\ \rho\eta\varGamma, & P_\mathrm{s}|h_{\mathrm{SR}_n}|^2 > \varGamma, \end{cases} \quad (7)$$

where $\varGamma$ is the saturation threshold of the EH. Without loss of generality, all WPR nodes are assumed to have the same saturation threshold. If the received power level at R_n, i.e., $P_\mathrm{s}|h_{\mathrm{SR}_n}|^2$, is smaller than $\varGamma$, the EH works in a linear mode. Otherwise, the EH outputs a constant power level of $\rho\eta\varGamma$. Next, the instantaneous SNRs at Bob and Eve are respectively

$$\gamma_\mathrm{D} = \frac{P_{\mathrm{R}_n}|h_{\mathrm{R}_n\mathrm{D}}|^2}{N_0}, \quad \gamma_{\mathrm{E}_2} = \frac{P_{\mathrm{R}_n}|h_{\mathrm{R}_n\mathrm{E}}|^2}{N_0}.$$

3 Secrecy outage analysis

The instantaneous achievable secrecy capacity for the Alice-R_n link can be expressed as

$$C_{\mathrm{SR}_n} = \left\{\frac{1}{2}\left(\log_2(1+\gamma_{\mathrm{R}_n}) - \log_2(1+\gamma_{\mathrm{E}_1})\right)\right\}^+, \quad (8)$$

where $\{x\}^+ = \max\{x, 0\}$. In the DF protocol, the relay can successfully decode Alice's information if the secrecy capacity for the Alice-R_n link is not less than a target secrecy capacity R_s, i.e., $C_{\mathrm{SR}_n} \ge R_\mathrm{s}$. Assuming that the relay can successfully decode Alice's information, the instantaneous secrecy capacity for the R_n-Bob link is

$$C_{\mathrm{R}_n\mathrm{D}} = \left\{\frac{1}{2}\left(\log_2(1+\gamma_\mathrm{D}) - \log_2(1+\gamma_{\mathrm{E}_2})\right)\right\}^+. \quad (9)$$

Secrecy outage occurs if either C_{SR_n} or $C_{\mathrm{R}_n\mathrm{D}}$ is smaller than the target secrecy rate R_s. The relay, which results in the Kth largest secrecy capacity for the Alice-R_n-Bob link, is selected to assist the transmission. Thus, the instantaneous secrecy capacity based on the Kth max-min criterion is

$$C_\mathrm{s} = K^{\mathrm{th}} \max_{n\in\{1,2,\ldots,N\}} \min(C_{\mathrm{SR}_n}, C_{\mathrm{R}_n\mathrm{D}}). \quad (10)$$

Thus, the SOP can be expressed as

$$\begin{aligned} P_{\mathrm{SOP}} &= \Pr(C_\mathrm{s} < R_\mathrm{s}) \\ &= \Pr\left(K^{\mathrm{th}} \max_{n\in\{1,2,\ldots,N\}} \min(C_{\mathrm{SR}_n}, C_{\mathrm{R}_n\mathrm{D}}) < R_\mathrm{s}\right) \\ &= \sum_{k=1}^{K} \binom{N}{k-1} \left(\Pr(\min(C_{\mathrm{SR}_n}, C_{\mathrm{R}_n\mathrm{D}}) < R_\mathrm{s})\right)^{N-k+1} \\ &\quad \cdot \left(1 - \Pr(\min(C_{\mathrm{SR}_n}, C_{\mathrm{R}_n\mathrm{D}}) < R_\mathrm{s})\right)^{k-1}, \end{aligned} \quad (11)$$

where

$$\begin{aligned}&\Pr(\min(C_{\mathrm{SR}_n}, C_{\mathrm{R}_n\mathrm{D}}) < R_{\mathrm{s}})\\&= 1-\Pr(\min(C_{\mathrm{SR}_n}, C_{\mathrm{R}_n\mathrm{D}}) \geq R_{\mathrm{s}})\\&= 1-\Pr(C_{\mathrm{SR}_n} \geq R_{\mathrm{s}}, C_{\mathrm{R}_n\mathrm{D}} \geq R_{\mathrm{s}}). \quad (12)\end{aligned}$$

Substituting γ_{R_n}, γ_{E_1}, γ_{E_2}, and γ_{D} into Eq. (12), we have

$$\Pr(C_{\mathrm{SR}_n} \geq R_{\mathrm{s}}, C_{\mathrm{R}_n\mathrm{D}} \geq R_{\mathrm{s}}) = M_1 + M_2, \quad (13)$$

where

$$M_1 = \Pr\left(x \geq A + By,\ xz \geq C,\ x \leq \frac{\varGamma}{P_{\mathrm{s}}}\right), \quad (14)$$

$$M_2 = \Pr\left(x \geq A + By,\ w \geq D + av,\ x > \frac{\varGamma}{P_{\mathrm{s}}}\right), \quad (15)$$

with

$$\begin{aligned}&\alpha = 2^{2R_{\mathrm{s}}},\ x = |h_{\mathrm{SR}_n}|^2,\ y = |h_{\mathrm{SE}}|^2,\ w = |h_{\mathrm{R}_n\mathrm{D}}|^2,\\&v = |h_{\mathrm{R}_n\mathrm{E}}|^2,\ z = w - av,\ C = \frac{(\alpha-1)N_0}{\rho\eta P_{\mathrm{s}}},\\&A = \frac{(\alpha-1)((1-\rho)N_0 + \sigma_n^2)}{(1-\rho)P_{\mathrm{s}}},\ D = \frac{(\alpha-1)N_0}{\rho\eta\varGamma},\\&B = \frac{\alpha((1-\rho)N_0 + \sigma_n^2)}{(1-\rho)N_0}.\end{aligned}$$

The PDF of z can be obtained as

$$f_z(z) = \begin{cases}\dfrac{\lambda_{\mathrm{R}_n\mathrm{D}}\lambda_{\mathrm{R}_n\mathrm{E}}}{\lambda_{\mathrm{R}_n\mathrm{D}} + \lambda_{\mathrm{R}_n\mathrm{E}}}\exp(-\lambda_{\mathrm{R}_n\mathrm{D}}z), & z \geq 0,\\ \dfrac{\lambda_{\mathrm{R}_n\mathrm{D}}\lambda_{\mathrm{R}_n\mathrm{E}}}{\lambda_{\mathrm{R}_n\mathrm{D}} + \lambda_{\mathrm{R}_n\mathrm{E}}}\exp(\lambda_{\mathrm{R}_n\mathrm{E}}z), & z < 0,\end{cases} \quad (16)$$

where $\lambda_{\mathrm{R}_n\mathrm{D}} = \dfrac{1}{g_{\mathrm{RD}}}$ and $\lambda_{\mathrm{R}_n\mathrm{E}} = \dfrac{1}{\alpha g_{\mathrm{RE}}}$.

Since both x and C in Eq. (14) are non-negative, to let the inequality $xz \geq C$ in Eq. (14) hold, z must be non-negative, too. Thus, M_1 can be re-expressed as

$$\begin{aligned}M_1 &= \Pr\left(x \geq A + By,\ x \geq \frac{C}{z},\ x \leq \frac{\varGamma}{P_{\mathrm{s}}},\ z > 0\right)\\&= \frac{\lambda_{\mathrm{R}_n\mathrm{E}}}{\lambda_{\mathrm{R}_n\mathrm{D}} + \lambda_{\mathrm{R}_n\mathrm{E}}}I_1 - I_2, \quad (17)\end{aligned}$$

where

$$I_1 = \Pr\left(x \geq A + By,\ x \leq \frac{\varGamma}{P_{\mathrm{s}}}\right), \quad (18)$$

$$I_2 = \Pr\left(x \geq A + By,\ x < \frac{C}{z},\ x \leq \frac{\varGamma}{P_{\mathrm{s}}},\ z > 0\right). \quad (19)$$

In what follows, we will calculate I_1 and I_2. One can re-write I_1 as

$$\begin{aligned}I_1 &= \Pr\left(A + By \leq x \leq \frac{\varGamma}{P_{\mathrm{s}}}\right)\\&= \int_0^{\frac{\varGamma}{BP_{\mathrm{s}}} - \frac{A}{B}}\int_{A+By}^{\frac{\varGamma}{P_{\mathrm{s}}}} f_{|h_{\mathrm{SR}_n}|^2}(x) f_{|h_{\mathrm{SE}}|^2}(y)\mathrm{d}x\mathrm{d}y\\&= \int_0^{\frac{\varGamma - AP_{\mathrm{s}}}{BP_{\mathrm{s}}}}\left(F_{|h_{\mathrm{SR}_n}|^2}\left(\frac{\varGamma}{P_{\mathrm{s}}}\right) - F_{|h_{\mathrm{SR}_n}|^2}(A+By)\right)\\&\quad\cdot\lambda_{\mathrm{SE}}\exp(-y\lambda_{\mathrm{SE}})\mathrm{d}y\\&= \left(1 - \exp\left(-\frac{(\varGamma - AP_{\mathrm{s}})(\lambda_{\mathrm{SE}} + B\lambda_{\mathrm{SR}_n})}{BP_{\mathrm{s}}}\right)\right)\\&\quad\cdot\frac{\lambda_{\mathrm{SE}}\exp(-A\lambda_{\mathrm{SR}_n})}{\lambda_{\mathrm{SE}} + B\lambda_{\mathrm{SR}_n}} - \exp\left(-\frac{\varGamma\lambda_{\mathrm{SR}_n}}{P_{\mathrm{s}}}\right)\\&\quad\cdot\left(1 - \exp\left(-\frac{(\varGamma - AP_{\mathrm{s}})\lambda_{\mathrm{SE}}}{BP_{\mathrm{s}}}\right)\right), \quad (20)\end{aligned}$$

where $\lambda_{\mathrm{SE}} = \dfrac{1}{g_{\mathrm{SE}}}$ and $\lambda_{\mathrm{SR}_n} = \dfrac{1}{g_{\mathrm{SR}}}$. I_2 can be written as

$$I_2 = I_{2A} + I_{2B}, \quad (21)$$

where

$$I_{2A} = \Pr\left(x \geq A + By,\ x < \frac{C}{z},\ \frac{C}{z} < \frac{\varGamma}{P_{\mathrm{s}}},\ z > 0\right), \quad (22)$$

$$I_{2B} = \Pr\left(x \geq A + By,\ x < \frac{\varGamma}{P_{\mathrm{s}}},\ \frac{C}{z} \geq \frac{\varGamma}{P_{\mathrm{s}}},\ z > 0\right). \quad (23)$$

Substituting Eqs. (1) and (16) into Eq. (22), I_{2A} can be further expressed as

$$\begin{aligned}I_{2A} &= \Pr\left(A + By \leq x < \frac{C}{z},\ z > \frac{CP_{\mathrm{s}}}{\varGamma}\right)\\&= \int_{\frac{CP_{\mathrm{s}}}{\varGamma}}^{\infty}\int_0^{\frac{C}{zB} - \frac{A}{B}}\Bigg[\exp(-\lambda_{\mathrm{SR}_n}(A + By))\\&\quad - \exp\left(-\lambda_{\mathrm{SR}_n}\left(\frac{C}{z}\right)\right)\Bigg]f_{|h_{\mathrm{SE}}|^2}(y)f_z(z)\mathrm{d}y\mathrm{d}z\\&= I_{2A_1} - I_{2A_2}, \quad (24)\end{aligned}$$

in which

$$I_{2A_1} = \frac{\exp(-A\lambda_{\mathrm{SR}_n})\lambda_{\mathrm{SE}}\lambda_{\mathrm{R}_n\mathrm{D}}\lambda_{\mathrm{R}_n\mathrm{E}}}{(\lambda_{\mathrm{R}_n\mathrm{D}}+\lambda_{\mathrm{R}_n\mathrm{E}})(B\lambda_{\mathrm{SR}_n}+\lambda_{\mathrm{SE}})} \cdot \Bigg[\frac{1}{\lambda_{\mathrm{R}_n\mathrm{D}}}\exp\left(-\frac{\lambda_{\mathrm{R}_n\mathrm{D}}CP_{\mathrm{s}}}{\varGamma}\right) - \int_{\frac{CP_{\mathrm{s}}}{\varGamma}}^{\infty}\exp\left(A\lambda_{\mathrm{SR}_n}+\frac{A\lambda_{\mathrm{SE}}}{B}\right) \cdot \exp\left(-z\lambda_{\mathrm{R}_n\mathrm{D}}-\frac{C\lambda_{\mathrm{SR}_n}+C\lambda_{\mathrm{SE}}/B}{z}\right)\mathrm{d}z\Bigg], \tag{25}$$

$$I_{2A_2} = \Bigg[\int_{\frac{CP_{\mathrm{s}}}{\varGamma}}^{\infty}\exp\left(-\frac{C\lambda_{\mathrm{SR}_n}}{z}-z\lambda_{\mathrm{R}_n\mathrm{D}}\right)\mathrm{d}z - \int_{\frac{CP_{\mathrm{s}}}{\varGamma}}^{\infty}\exp\left(-z\lambda_{\mathrm{R}_n\mathrm{D}}-\frac{C\lambda_{\mathrm{SR}_n}+C\lambda_{\mathrm{SE}}/B}{z}\right) \cdot \exp\left(\frac{A\lambda_{\mathrm{SE}}}{B}\right)\mathrm{d}z\Bigg]\frac{\lambda_{\mathrm{R}_n\mathrm{D}}\lambda_{\mathrm{R}_n\mathrm{E}}}{\lambda_{\mathrm{R}_n\mathrm{D}}+\lambda_{\mathrm{R}_n\mathrm{E}}}. \tag{26}$$

Using Eq. (3.324.1) in Gradshteyn and Ryzhik (2007), I_{2A_1} and I_{2A_2} can be simplified into

$$I_{2A_1} = \frac{\exp(-A\lambda_{\mathrm{SR}_n})\lambda_{\mathrm{SE}}\lambda_{\mathrm{R}_n\mathrm{D}}\lambda_{\mathrm{R}_n\mathrm{E}}}{(\lambda_{\mathrm{R}_n\mathrm{D}}+\lambda_{\mathrm{R}_n\mathrm{E}})(B\lambda_{\mathrm{SR}_n}+\lambda_{\mathrm{SE}})} \cdot \left(\frac{\exp(-CP_{\mathrm{s}}\lambda_{\mathrm{R}_n\mathrm{D}}/\varGamma)}{\lambda_{\mathrm{R}_n\mathrm{D}}}-E+F\right), \tag{27}$$

$$I_{2A_2} = \left(G-H-\exp\left(\frac{A\lambda_{\mathrm{SE}}}{B}\right)(E-F)\right) \cdot \frac{\lambda_{\mathrm{R}_n\mathrm{D}}\lambda_{\mathrm{R}_n\mathrm{E}}}{\lambda_{\mathrm{R}_n\mathrm{D}}+\lambda_{\mathrm{R}_n\mathrm{E}}}, \tag{28}$$

respectively, where

$$E = 2\sqrt{\frac{C(B\lambda_{\mathrm{SR}_n}+\lambda_{\mathrm{SE}})}{B\lambda_{\mathrm{R}_n\mathrm{D}}}} \cdot K_1\left(2\sqrt{\frac{C\lambda_{\mathrm{R}_n\mathrm{D}}(B\lambda_{\mathrm{SR}_n}+\lambda_{\mathrm{SE}})}{B}}\right), \tag{29}$$

$$F = \int_0^{\frac{CP_{\mathrm{s}}}{\varGamma}}\exp\left(-z\lambda_{\mathrm{R}_n\mathrm{D}}-\frac{C}{Bz}(B\lambda_{\mathrm{SR}_n}+\lambda_{\mathrm{SE}})\right)\mathrm{d}z, \tag{30}$$

$$G = 2\sqrt{\frac{C\lambda_{\mathrm{SR}_n}}{\lambda_{\mathrm{R}_n\mathrm{D}}}}K_1\left(2\sqrt{C\lambda_{\mathrm{SR}_n}\lambda_{\mathrm{R}_n\mathrm{D}}}\right), \tag{31}$$

$$H = \int_0^{\frac{CP_{\mathrm{s}}}{\varGamma}}\exp\left(-z\lambda_{\mathrm{R}_n\mathrm{D}}-\frac{C\lambda_{\mathrm{SR}_n}}{z}\right)\mathrm{d}z, \tag{32}$$

in which $K_1(\cdot)$ is the first-order modified Bessel function of the second kind. Note that F and H can be easily obtained using numerical calculation by replacing integrations with summations.

Similarly, one has I_{2B} as

$$\begin{aligned} I_{2B} &= \Pr\left(A+By\le x\le\frac{\varGamma}{P_{\mathrm{s}}},\ 0<z\le\frac{CP_{\mathrm{s}}}{\varGamma}\right) \\ &= \Pr\left(A+By\le x\le\frac{\varGamma}{P_{\mathrm{s}}}\right)\Pr\left(0<z\le\frac{CP_{\mathrm{s}}}{\varGamma}\right) \\ &= I_1\Pr\left(0<z\le\frac{CP_{\mathrm{s}}}{\varGamma}\right), \end{aligned} \tag{33}$$

where

$$\Pr\left(0<z\le\frac{CP_{\mathrm{s}}}{\varGamma}\right) = \frac{\lambda_{\mathrm{R}_n\mathrm{E}}}{\lambda_{\mathrm{R}_n\mathrm{D}}+\lambda_{\mathrm{R}_n\mathrm{E}}}\cdot\left(1-\exp\left(-\frac{CP_{\mathrm{s}}\lambda_{\mathrm{R}_n\mathrm{D}}}{\varGamma}\right)\right). \tag{34}$$

Next, M_2 can be re-expressed as

$$\begin{aligned} M_2 &= \Pr\left(x\ge A+By,\ x>\frac{\varGamma}{P_{\mathrm{s}}}\right)\Pr(w\ge D+av) \\ &= (Q_1+Q_2)\Pr(w\ge D+av), \end{aligned} \tag{35}$$

where

$$\begin{aligned} Q_1 &= \Pr\left(x\ge A+By,\ A+By>\frac{\varGamma}{P_{\mathrm{s}}}\right) \\ &= \int_{\frac{\varGamma-AP_{\mathrm{s}}}{BP_{\mathrm{s}}}}^{\infty}\int_{A+By}^{\infty} f_{|h_{\mathrm{SR}_n}|^2}(x)f_{|h_{\mathrm{SE}}|^2}(y)\mathrm{d}x\mathrm{d}y \\ &= \frac{\exp(-A\lambda_{\mathrm{SR}_n})}{B\lambda_{\mathrm{SR}_n}+\lambda_{\mathrm{SE}}}\exp\left(-\frac{(\varGamma-AP_{\mathrm{s}})(B\lambda_{\mathrm{SR}_n}+\lambda_{\mathrm{SE}})}{BP_{\mathrm{s}}}\right), \end{aligned} \tag{36}$$

$$\begin{aligned} Q_2 &= \Pr\left(x>\frac{\varGamma}{P_{\mathrm{s}}},\ A+By<\frac{\varGamma}{P_{\mathrm{s}}}\right) \\ &= \int_0^{\frac{\varGamma-AP_{\mathrm{s}}}{BP_{\mathrm{s}}}}\int_{\frac{\varGamma}{P_{\mathrm{s}}}}^{\infty} f_{|h_{\mathrm{SR}_n}|^2}(x)f_{|h_{\mathrm{SE}}|^2}(y)\mathrm{d}x\mathrm{d}y \\ &= \exp\left(-\frac{\varGamma\lambda_{\mathrm{SR}_n}}{P_{\mathrm{s}}}\right)\left(1-\exp\left(-\frac{(\varGamma-AP_{\mathrm{s}})\lambda_{\mathrm{SE}}}{BP_{\mathrm{s}}}\right)\right). \end{aligned} \tag{37}$$

Furthermore, the expression of $\Pr(w\ge D+av)$ can be obtained as

$$\begin{aligned} &\Pr(w\ge D+av) \\ &= \int_0^{\infty}\int_{D+av}^{\infty} f_{|h_{\mathrm{R}_n\mathrm{D}}|^2}(w)f_{|h_{\mathrm{R}_n\mathrm{E}}|^2}(v)\mathrm{d}w\mathrm{d}v \\ &= \frac{\lambda_{\mathrm{RE}}}{\lambda_{\mathrm{R}_n\mathrm{D}}+\lambda_{\mathrm{RE}}}\exp(-D\lambda_{\mathrm{R}_n\mathrm{D}}). \end{aligned} \tag{38}$$

Finally, one has SOP by substituting Eqs. (17) and (35) into Eq. (11).

4 Numerical results and discussion

In this section, we present numerical results. Unless otherwise explicitly specified, the parameters of those results are set as follows: $N = 3$, $K = 2$, $R_{\rm s} = 0.3$ bits/(s·Hz), $P_{\rm s}/N_0 = 30$ dB, $g_{\rm SR} = 1$, $g_{\rm SE} = 0.02$, $\eta = 0.9$, $\rho = 0.5$, $\Gamma/P_{\rm s} = -5$ dB, $\sigma_n^2 = N_0$ ($n \in \{1, 2, \ldots, N\}$), and $\beta = g_{\rm RD}/g_{\rm RE}$.

In Fig. 1, we present the analytical results and the Monte-Carlo simulations for SOP vs. β under various numbers of relays N. One can see that simulation results match the analytical results, which validates the accuracy of the derived analytical expressions. We can also observe that the SOP performance with a larger N outperforms that with a smaller one. This is because the opportunity of successfully selecting the Kth best relay is high when the number of WPR nodes N increases.

As depicted in Fig. 2, the SOP with a smaller K is superior to that with a larger one. This is because a smaller K means that a better relay can be selected to assist the Alice-Bob transmission.

In Fig. 3, it is observed that the SOP can be improved by increasing the value of Γ. It is because under the condition that the received power is greater than the saturation threshold of the energy harvester at the relay, i.e., $P_{\rm s}|h_{\rm SR}|^2 > \Gamma$, a higher Γ means that more energy can be harvested at the relay for broadcasting information to Bob. Thus, the SOP is better. However, one can also see from Fig. 3 that this does not always hold with the increment of Γ. There exists a particular value of Γ, i.e., $\Gamma/P_{\rm s} = 0$ dB, in Fig. 3, and we find that the SOP performance will not be improved when Γ is beyond that value. This particular value is the maximum level of power harvested from Alice.

As shown in Fig. 4, there is an optimal value of ρ, at which the SOP performance is the best. This is because as ρ increases, a larger portion of power can be used to harvest the relay for broadcasting information in the second phase. Therefore, the SOP performance can be improved. However, at the same time, the portion of power used for decoding purpose is reduced. When that power is below a certain

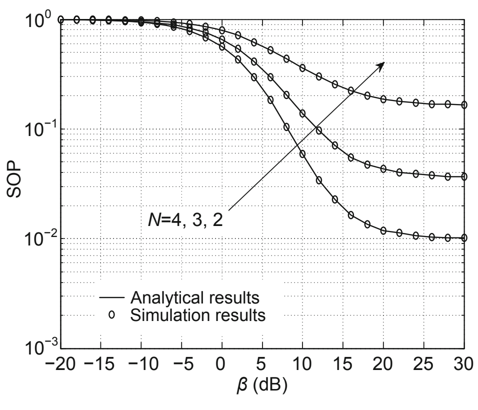

Fig. 1 SOP vs. β for various N

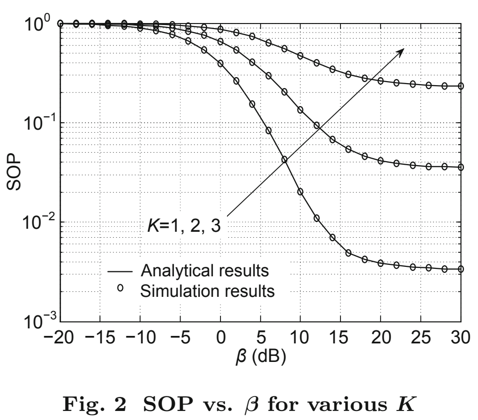

Fig. 2 SOP vs. β for various K

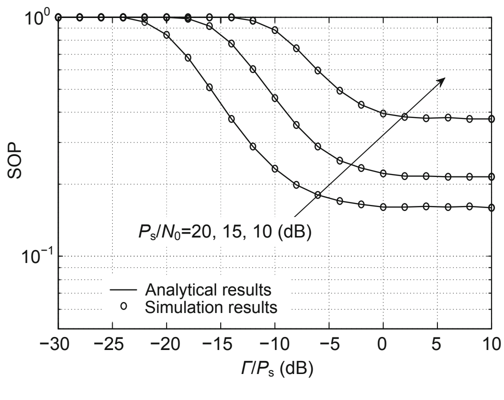

Fig. 3 SOP vs. $\Gamma/P_{\rm s}$ for various $P_{\rm s}/N_0$

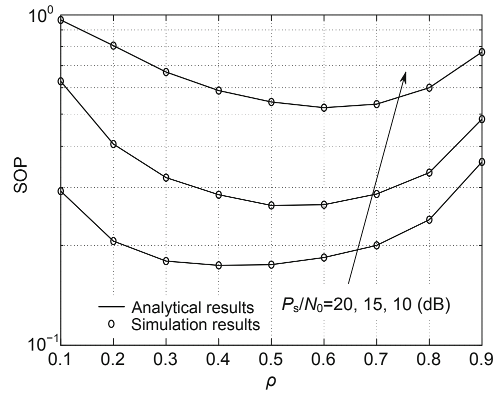

Fig. 4 SOP vs. ρ for various $P_{\rm s}/N_0$

level, information can no longer be decoded correctly, which leads to a worse SOP performance.

In Fig. 5, we can observe that a higher η leads to better SOP performance as more energy can be used in the second phase at a higher energy conversion efficiency.

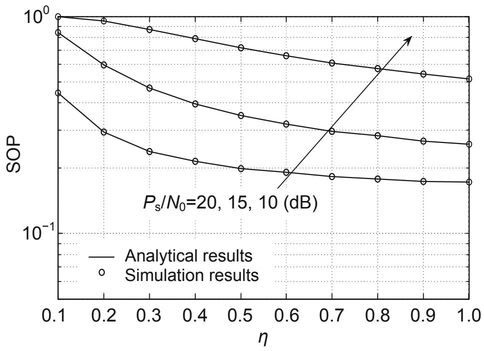

Fig. 5 SOP vs. η for various P_s/N_0

5 Conclusions

In this paper, we have investigated the secrecy performance for wireless-powered relaying in cooperative systems. The Kth best relay has been selected to assist the source-relay-destination transmission. Considering the relays with nonlinear energy harvesters, the analytical expression for the secrecy outage probability has been derived, and has also been verified via simulation.

References

Boshkovska, E., Ng, D.W.K., Zlatanov, N., *et al.*, 2015. Practical non-linear energy harvesting model and resource allocation for SWIPT systems. *IEEE Commun. Lett.*, **19**(12):2082-2085. http://dx.doi.org/10.1109/LCOMM.2015.2478460

Chen, Y., 2016. Energy harvesting AF relaying in the presence of interference and Nakagami-m fading. *IEEE Trans. Wirel. Commun.*, **15**(2):1008-1017. http://dx.doi.org/10.1109/TWC.2015.2481393

Ding, Z., Krikidis, I., Sharif, B., *et al.*, 2014a. Wireless information and power transfer in cooperative networks with spatially random relays. *IEEE Trans. Wirel. Commun.*, **13**(8):4440-4453. http://dx.doi.org/10.1109/TWC.2014.2314114

Ding, Z., Perlaza, S.M., Esnaola, I., *et al.*, 2014b. Power allocation strategies in energy harvesting wireless cooperative networks. *IEEE Trans. Wirel. Commun.*, **13**(2):846-860. http://dx.doi.org/10.1109/TWC.2013.010213.130484

Ding, Z., Zhong, C., Ng, D.W.K., *et al.*, 2015. Application of smart antenna technologies in simultaneous wireless information and power transfer. *IEEE Commun. Mag.*, **53**(4):86-93. http://dx.doi.org/10.1109/MCOM.2015.7081080

Dong, Y., Hossain, M.J., Cheng, J., 2016. Performance of wireless powered amplify and forward relaying over Nakagami-m fading channels with nonlinear energy harvester. *IEEE Commun. Lett.*, **20**(4):672-675. http://dx.doi.org/10.1109/LCOMM.2016.2528260

Gradshteyn, I.S., Ryzhik, I.M., 2007. Table of Integrals, Series, and Products (7th Ed.). Academic Press, USA.

Gu, Y., Aïssa, S., 2015. RF-based energy harvesting in decode-and-forward relaying systems: ergodic and outage capacities. *IEEE Trans. Wirel. Commun.*, **14**(11):6425-6434. http://dx.doi.org/10.1109/TWC.2015.2453418

Krikidis, I., Timotheou, S., Nikolaou, S., *et al.*, 2014. Simultaneous wireless information and power transfer in modern communication systems. *IEEE Commun. Mag.*, **52**(11):104-110. http://dx.doi.org/10.1109/MCOM.2014.6957150

Mo, J., Tao, M., Liu, Y., 2012. Relay placement for physical layer security: a secure connection perspective. *IEEE Commun. Lett.*, **16**(6):878-881. http://dx.doi.org/10.1109/LCOMM.2012.042312.120582

Ng, D.W.K., Lo, E.S., Schober, R., 2014. Robust beamforming for secure communication in systems with wireless information and power transfer. *IEEE Trans. Wirel. Commun.*, **13**(8):4599-4615. http://dx.doi.org/10.1109/TWC.2014.2314654

Pan, G., Tang, C., Li, T., *et al.*, 2015. Secrecy performance analysis for SIMO simultaneous wireless information and power transfer systems. *IEEE Trans. Commun.*, **63**(9):3423-3433. http://dx.doi.org/10.1109/TCOMM.2015.2458317

Proakis, J.G., 2000. Digital Communications (4th Ed.). McGraw-Hill, USA.

Wang, H.M., Xia, X.G., 2015. Enhancing wireless secrecy via cooperation: signal design and optimization. *IEEE Commun. Mag.*, **53**(12):47-53. http://dx.doi.org/10.1109/MCOM.2015.7355565

Zhang, J.L., Pan, G.F., Wang, H.M., 2016. On physical-layer security in underlay cognitive radio networks with full-duplex wireless-powered secondary system. *IEEE Access*, **4**:3887-3893. http://dx.doi.org/10.1109/ACCESS.2016.2591782

Zhou, Y., Pan, G., Li, T., *et al.*, 2015. Secrecy outage performance for partial relay selection schemes in cooperative systems. *IET Commun.*, **9**(16):1980-1987. http://dx.doi.org/10.1049/iet-com.2015.0109

Zou, Y., Wang, X., Shen, W., 2013. Optimal relay selection for physical-layer security in cooperative wireless networks. *IEEE J. Sel. Areas Commun.*, **31**(10):2099-2111. http://dx.doi.org/10.1109/JSAC.2013.131011

Zou, Y., Champagne, B., Zhu, W.P., *et al.*, 2015a. Relay-selection improves the security-reliability trade-off in cognitive radio systems. *IEEE Trans. Commun.*, **63**(1):215-228. http://dx.doi.org/10.1109/TCOMM.2014.2377239

Zou, Y., Zhu, J., Wang, X., *et al.*, 2015b. Improving physical-layer security in wireless communications using diversity techniques. *IEEE Netw.*, **29**(1):42-48. http://dx.doi.org/10.1109/MNET.2015.7018202