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Improving Physical Layer Security of Cooperative NOMA System with Wireless-Powered Full-Duplex Relaying

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Abstract: Non-orthogonal multiple access (NOMA) and wireless energy harvesting are two promising technologies for improving spectral efficiency and energy efficiency, respectively. In this paper, we study the physical layer security of a wireless-powered full-duplex (FD) relay-aided cooperative NOMA system. In particular, the source is wiretapped by an eavesdropper, and the FD relay assists the transmission from the source to a near user and a far user with self-energy recycling. To enhance the security performance of the system, we propose an artificial noise (AN)-aided cooperative transmission scheme, in which the relay emits a jamming signal to confuse the eavesdropper while receiving the signal from the source. For the proposed scheme, the ergodic secrecy sum rate (ESSR) is derived to characterize the secrecy performance and a lower bound of ESSR is obtained. Finally, numerical results verify the accuracy of the theoretical analysis of the proposed AN-aided secure transmission scheme. The superiority of the proposed scheme is also demonstrated since this scheme can achieve better secrecy performance, compared to the conventional cooperative NOMA scheme.

Keywords: non-orthogonal multiple access; wireless-powered relaying; physical layer security; full duplex; artificial noise

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1. Introduction

With the development of the Internet of Things (IoT), the number of data traffics originated from wireless data services is exploding, which requires the 5G mobile communication system to satisfy higher spectral efficiency (SE), lower transmission delay, and higher reliability. Non-orthogonal multiple access (NOMA) can be applied in the power domain and significantly improves SE by using superposition coding and successive interference cancellation (SIC) techniques to serve multiple users simultaneously in the same time/frequency/code resource block. Full duplex (FD) is also a technique that can effectively improve SE. In particular, according to its characteristics, the FD relay is able to transmit and receive signals simultaneously [1]. Therefore, combining NOMA with FD has received increasing attention from both industry and academia [2].

Wireless energy harvesting (EH) is a promising technology for extending the lifetime of wireless nodes and improving energy efficiency in energy-constrained scenarios and can harvest energy from radio frequency signals [3]. In this regard, wireless EH has been conducted in half-duplex relaying systems to boost energy efficiency. Moreover, for FD relaying system, the self-interference can be viewed as an extra power source to facilitate wireless EH. The combination of wireless-powered FD technology and NOMA improves the SE of the system and provides energy supply to the energy-constrained nodes to increase their working time, which deserves significant attention and investigation. In [4], Yang et al. considered a decode-and-forward (DF) FD wireless relay network with self-energy recycling and analyzed the outage probability performance of this system. In [5], Liu et al. proposed a new cooperative NOMA scheme with simultaneous wireless information and power transfer (SWIPT), where the user close to the transmitter worked as a wireless-powered relay to help the far user. The authors in [6] investigated the outage performance of NOMA-based cooperative relaying systems, where SWIPT was applied at the near user to help the far user for data transmission. Moreover, in [7], Guo et al. proposed a cooperative NOMA network with EH and FD relay, which could effectively reduce the outage probability and improve the ergodic rate.

On the other hand, the security performance of wireless networks faces a great challenge due to the broadcast nature of wireless channels. Physical layer security (PLS) is an attractive approach to enhance information security by exploiting the inherent characteristics of wireless channels (e.g., fading, noise and interference) to ensure that eavesdroppers cannot wiretap legitimate information at the physical layer [8]. Therefore, PLS has been recognized as an effective method to enable secure communications. In recent years, many research interests have focused on dealing with the security issues in NOMA-enabled networks. In [9], Chen et al. analyzed the security performance of NOMA systems with cooperative relay, and the results indicated that amplify-and-forward (AF) and DF have almost the same impact on outage performance. In another study [10], Feng et al. proposed that the combination of FD and artificial noise (AN) techniques in cooperative NOMA networks can effectively reduce the secrecy outage probability (SOP). In [11], Liu et al. studied a cooperative NOMA system with the strong user as FD relay forwarding signals to the weak user, and the SOP could be improved by suppressing the self-interference (SI). Lv et al., in [12], considered a downlink and uplink cooperative NOMA system with an untrusted relay and proposed an AN-assisted method for enhancing the security performance. Lei et al., in [13], proposed three relay selection schemes in the NOMA network for Nakagami-m fading channels to improve SOP. Furthermore, in [14], Salem et al. investigated the secrecy performance of different relay selection schemes in cooperative NOMA systems, where the source node communicated with multiple users through multiple EH relays in the presence of passive eavesdroppers. Guo et al., in [15], analyzed the ergodic secrecy rate and SOP of a NOMA system with EH and FD relaying.

However, to the best of our knowledge, there are few works on the analysis of the secrecy performance of a cooperative NOMA system with wireless-powered FD relaying. Motivated by this, in this paper, we consider a cooperative NOMA system with wireless-powered FD relaying. The main contributions of this paper are summarized as follows:

- We investigate a cooperative NOMA system with wireless-powered FD relaying. In particular, an AN-aided secrecy enhancing scheme is proposed for self-sustained FD relay to reduce the decoding performance of the eavesdropper, where the FD relay can harvest energy from the source and SI signal.
- For the proposed AN-aided secrecy enhancing scheme, the lower bound of the ergodic secrecy sum rate (ESSR) is analyzed with closed-form expressions. In particular, the proposed scheme achieves a positive lower bound of ESSR, indicating that perfect secrecy can be guaranteed.
- Monte Carlo simulations are provided to verify the accuracy of the theoretical analysis, and the superiority of the proposed AN-aided secure transmission scheme over the benchmark scheme is also presented. This indicates that adopting AN at the wireless-powered FD relay can significantly improve the secrecy performance in the cooperative NOMA systems.

The rest of the paper is organized as follows. Section 2 introduces the system model and the AN-aided secure transmission scheme. Section 3 analyzes the ESSR of our proposed scheme. Numerical results are evaluated in Section 4. Finally, the paper is concluded in Section 5.

2. System Model and the Proposed Scheme

2.1. System Model

As shown in Figure 1, we consider secure communications in a wireless-powered FD-relay-aided cooperative NOMA system. It consists of a source S, a DF relay R, two users (the near user U_1 and the far user U_2), and an eavesdropper E. It is assumed that direct links between the source and the two users do not exist due to the shadow fading. The source, two users, and the eavesdropper are all equipped with a single antenna, whereas the relay is equipped with two antennas for receiving and transmitting simultaneously. We assume that the eavesdropper can wiretap the transmitted signals from the source and have the SIC ability, i.e., E will decode the signal of the far user U_2 before decoding the signal of the near user U_1.

The whole transmission block time T is divided into two equal phases. In the first phase, the source transmits superposed signals to the relay, which adopts power splitting (PS) for EH and information decoding (ID). Relay is equipped with a battery that has sufficient initial power to supply transmission consumption before EH. At the same time, the FD relay emits AN to the eavesdropper, and the two users keep silent. In the second phase, the source only transmits energy symbol to the relay, and the relay employs DF protocol to forward signals to the two NOMA users while conducting EH from the source.

We consider Rayleigh fading channels. The channel coefficients between the links $S \to R$, $R \to U_1$, $R \to U_2$, $R \to E$, and $S \to E$ are denoted as h_{sr}, h_{ru_1}, h_{ru_2}, h_{se}, and h_{re}, respectively. We assume that all channels in the system obey independent complex Gaussian distribution with zero mean and variance ε_{sr}, ε_{ru_1}, ε_{ru_2}, ε_{se}, and ε_{re}, respectively. The corresponding channel gains are denoted as $g_{sr} = |h_{sr}|^2$, $g_{ru_1} = |h_{ru_1}|^2$, $g_{ru_2} = |h_{ru_2}|^2$, $g_{se} = |h_{se}|^2$, and $g_{re} = |h_{re}|^2$, respectively. The additive Gaussian white noise of R, U_1, U_2, and E are denoted as n_r, n_{u_1}, n_{u_2}, and n_e, respectively, and all of them are with mean zero and variance σ^2. The whole transmit power of S is P_s, and the signal-to-noise ratio (SNR) of the system is defined as $\rho = \frac{P_s}{\sigma^2}$.

2.2. Proposed Scheme

In this subsection, we discuss the joint time and power allocation scheme in the cooperative NOMA network with wireless-powered FD relaying and propose an AN-aided secure transmission scheme to guarantee the secrecy performance of the system.

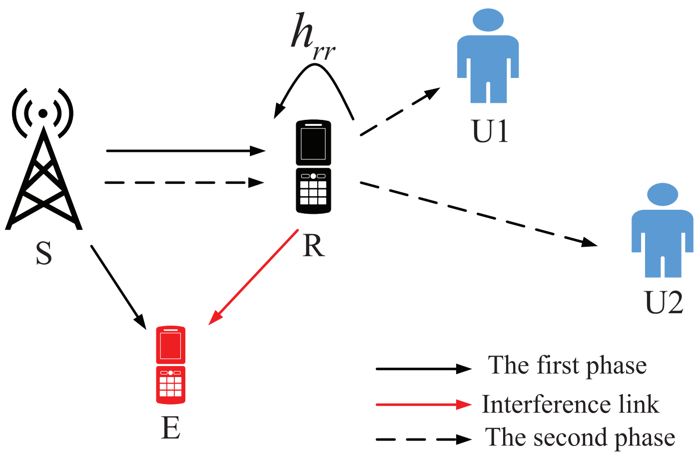

Figure 1. Cooperative NOMA system with wireless-powered FD relay.

In the first phase, the source emits superposed signals to the relay. The superposed signals can be expressed as

$$x_s = \sqrt{\alpha_1 P_s} x_1 + \sqrt{\alpha_2 P_s} x_2, \tag{1}$$

where x_1 and x_2 are information symbols for U_1 and U_2, respectively; α_1 and α_2 are power allocation factors for user U_1 and user U_2, respectively, satisfying $\alpha_1 < \alpha_2$ and $\alpha_1 + \alpha_2 = 1$. FD relay harvests power from the received signal using PS architecture, i.e., the part of βP_s $(0 \le \beta \le 1)$ for EH and the rest part of $(1-\beta)P_s$ for ID. At the same time, the relay emits a jamming signal w to the eavesdropper, and the two users keep silent. Therefore, the signals received at the relay and the eavesdropper are given by

$$y_{1,r} = \sqrt{(1-\beta)}h_{sr}x_s + \sqrt{P_{1,r}}h_{rr}w + n_r, \tag{2}$$

$$y_e = h_{se}x_s + \sqrt{P_{1,r}}h_{re}w + n_e, \tag{3}$$

where h_{rr} is the SI channel and $P_{1,r}$ is the transmit power of R in the first phase.

The harvested energy at R in the first phase is given by

$$E_{1,r} = \frac{T}{2}\eta\left(\alpha_1\beta P_s|h_{sr}|^2 + \alpha_2\beta P_s|h_{sr}|^2 + P_{1,r}|h_{rr}|^2\right), \tag{4}$$

where η $(0 < \eta < 1)$ is the EH efficiency. The transmit power from R can be expressed as

$$P_{1,r} = \frac{\eta\beta P_s|h_{sr}|^2}{1-\eta|h_{rr}|^2}. \tag{5}$$

The relay decodes the signals of x_1 and x_2 according to SIC. In NOMA, the SIC decoding of each receiver always starts from a weak signal to a strong signal. The signal-to-interference-plus-noise ratio (SINR) of R for decoding x_1 and x_2 can be written as

$$\gamma_{sr}^{x_2} = \frac{(1-\beta)\alpha_2\rho_s|h_{sr}|^2}{(1-\beta)\alpha_1\rho_s|h_{sr}|^2 + \zeta\rho_{1,r} + 1}, \tag{6}$$

$$\gamma_{sr}^{x_1} = \frac{(1-\beta)\alpha_1\rho_s|h_{sr}|^2}{\zeta\rho_{1,r} + 1}, \tag{7}$$

where $\zeta \in [0,1]$ is the residual SI coefficient due to imperfect self-interference cancellation.

We assume that there is a worst-case eavesdropping at E, and E has decoded x_2 before starting to decode x_1. Thus, the received SINRs at E can be expressed as

$$\gamma_{se}^{x_2} = \frac{\alpha_2\rho_s|h_{se}|^2}{\alpha_1\rho_s|h_{se}|^2 + \rho_{1,r}|h_{re}|^2 + 1}, \tag{8}$$

$$\gamma_{se}^{x_1} = \frac{\alpha_1\rho_s|h_{se}|^2}{\rho_{1,r}|h_{re}|^2 + 1}. \tag{9}$$

In the second phase, the relay harvests energy from the source and transmits signals to the two users by using the DF protocol. Thus, the signals received at the relay, and two users can be expressed as

$$y_{2,r} = \sqrt{\beta P_s}h_{sr}x_e + \sqrt{P_{2,r}}h_{rr}v + n_r, \tag{10}$$

$$y_{u_1} = \sqrt{P_{2,r}}h_{ru_1}x_r + n_{u_1}, \tag{11}$$

$$y_{u_2} = \sqrt{P_{2,r}}h_{ru_2}x_r + n_{u_2}, \tag{12}$$

where x_e is the energy symbol, which can be viewed as a kind of friendly information from the source [16], v is the residual SI symbol of R, $P_{2,r}$ is the transmit power of R in the second phase and x_r is the superposed signal emitted by R.

The harvested energy at R in the second phase can be written as

$$E_{2,r} = \frac{T}{2}\eta\left(\alpha_1\beta P_s|h_{sr}|^2 + \alpha_2\beta P_s|h_{sr}|^2 + P_{2,r}|h_{rr}|^2\right). \tag{13}$$

The transmission power $P_{2,r}$ can be written as

$$P_{2,r} = \frac{\eta \beta P_s |h_{sr}|^2}{1 - \eta |h_{rr}|^2}. \tag{14}$$

In this phase, U_1 first decodes x_2 and subtracts it by SIC for decoding x_1. The corresponding SINR of U_1 for decoding x_1 and x_2 are given by

$$\gamma_{ru_1}^{x_2} = \frac{\alpha_2 \rho_{2,r} |h_{ru_1}|^2}{\alpha_1 \rho_{2,r} |h_{ru_1}|^2 + 1}, \tag{15}$$

$$\gamma_{ru_1}^{x_1} = \alpha_1 \rho_{2,r} |h_{ru_1}|^2. \tag{16}$$

U_2 treats x_1 as the interference and decodes x_2 by using the following SINR

$$\gamma_{ru_2}^{x_2} = \alpha_2 \rho_{2,r} |h_{ru_2}|^2. \tag{17}$$

3. Performance Analysis

In this section, we evaluate the secrecy performance based on the ESSR metric and study the ESSR of the proposed AN-aided secrecy enhancing scheme. As mentioned in [17], it is important to study ESSR when the target data rate is adjusted according to the user's channel conditions. The achievable rate at U_1 is obtained as

$$C_{su_1}^{x_1} = \frac{1}{2} \min\left[\log_2\left(1 + \gamma_{sr}^{x_1}\right), \log_2\left(1 + \gamma_{ru_1}^{x_1}\right)\right]. \tag{18}$$

The achievable rate at U_2 is given by

$$C_{su_2}^{x_2} = \frac{1}{2} \min\left[\log_2\left(1 + \gamma_{sr}^{x_2}\right), \log_2\left(1 + \gamma_{ru_2}^{x_2}\right), \log_2\left(1 + \gamma_{ru_1}^{x_2}\right)\right]. \tag{19}$$

The eavesdropping rate at E for x_1 and x_2 are

$$C_e^{x_1} = \frac{1}{2} \log_2\left(1 + \gamma_{se}^{x_1}\right), \tag{20}$$

$$C_e^{x_2} = \frac{1}{2} \log_2\left(1 + \gamma_{se}^{x_2}\right). \tag{21}$$

Since the eavesdropper E only wiretaps the signals from the source, the secrecy sum rate of the cooperative NOMA transmission can be mathematically formulated as

$$C_{ssr} = \left\{C_{sr}^{x_1} - C_e^{x_1}\right\}^+ + \left\{C_{sr}^{x_2} - C_e^{x_2}\right\}^+, \tag{22}$$

where $\{Y\}^+ = \max\{0, Y\}$.

ESSR is adopted as a performance metric. Based on (18), the lower bound of ESSR for cooperative NOMA transmission can be obtained by using Jensen's inequality, which can be written as

$$\begin{aligned} \mathbb{E}[C_{ssr}] &\geq C_{ssr,lb} \\ &\triangleq \left\{\mathbb{E}\left[C_{sr}^{x_1}\right] - \mathbb{E}\left[C_e^{x_1}\right]\right\}^+ + \left\{\mathbb{E}\left[C_{sr}^{x_2}\right] - \mathbb{E}\left[C_e^{x_2}\right]\right\}^+. \end{aligned} \tag{23}$$

Defining $Z_1 = \gamma_{sr}^{x_1}$, we can obtain its cumulative distribution function (CDF) as

$$\begin{aligned} F_{Z_1}(z_1) &= \Pr\left(\gamma_{sr}^{x_1} < z_1\right) \\ &= 1 - e^{\frac{-z_1(\zeta \rho_{1,r} + 1)}{(1-\beta)\alpha_1 \rho_s \varepsilon_{sr}}}. \end{aligned} \tag{24}$$

Based on (24), $\mathbb{E}\left[C_{sr}^{x_1}\right]$ can be calculated by

$$\begin{aligned}\mathbb{E}\left[C_{sr}^{x_1}\right] &= \int_0^\infty \frac{1-F_{Z_1}(z_1)}{2(1+z_1)}dz_1 \\ &= \frac{1}{2}\int_0^\infty \frac{e^{\frac{-z_1(\zeta\rho_{1,r}+1)}{(1-\beta)\alpha_1\rho_s\varepsilon_{sr}}}}{(1+z_1)}dz_1 \\ &= \frac{\pi}{2N}\sum_{n=1}^{N}\frac{\sqrt{1-z_n^2}}{2(1+z_n)}e^{\frac{-z_n(\zeta\rho_{1,r}+1)}{(1-\beta)\alpha_1\rho_s\varepsilon_{sr}}},\end{aligned} \tag{25}$$

where $z_n = \cos\left(\frac{2n-1}{2N}\pi\right)$.

The ESSR of wiretaping x_1 at E can be expressed as

$$\begin{aligned}\mathbb{E}\left[C_{e}^{x_1}\right] &= \frac{1}{2}\int_0^\infty\int_0^\infty \log\left(1+\frac{\alpha_1 u_{se}}{u_{re}+1}\right)f_{U_{se}}(u_{se})f_{U_{re}}(u_{re})du_{se}du_{re} \\ &= \frac{1}{2\rho_s\rho_{1,r}\varepsilon_{se}\varepsilon_{re}}\int_0^\infty\left(\int_0^\infty \log\left(1+\frac{\alpha_1 u_{se}}{u_{re}+1}\right)e^{-\frac{u_{se}}{\rho_s\varepsilon_{se}}}du_{se}\right)e^{-\frac{u_{re}}{\rho_{1,r}\varepsilon_{re}}}du_{re} \\ &= \frac{1}{2\rho_s\rho_{1,r}\varepsilon_{se}\varepsilon_{re}}\left[-\rho_s\varepsilon_{se}e^{\frac{1}{\alpha_1\rho_s\varepsilon_{se}}}\int_0^\infty e^{\frac{u_{re}}{\alpha_1\rho_s\varepsilon_{se}}-\frac{u_{re}}{\rho_{1,r}\varepsilon_{re}}}\mathrm{Ei}\left(-\frac{1+u_{re}}{\alpha_1\rho_s\varepsilon_{se}}\right)du_{re}\right] \\ &\overset{(a)}{\approx} \frac{\pi^2}{2N\rho_{1,r}\varepsilon_{re}}e^{\frac{1}{\alpha_1\rho_s\varepsilon_{se}}}\sum_{n=1}^{N}\sqrt{1-z_n^2}e^{\frac{\tan\theta_n}{\alpha_1\rho_s\varepsilon_{se}}-\frac{\tan\theta_n}{\rho_{1,r}\varepsilon_{re}}}\mathrm{Ei}\left(-\frac{1+\tan\theta_n}{\alpha_1\rho_s\varepsilon_{se}}\right)\sec\theta_n^2.\end{aligned} \tag{26}$$

where $U_{se} = \rho_s g_{se}$, $U_{re} = \rho_r g_{re}$; step (a) is obtained by changing variable $u_{re} = \tan\theta$; $\mathrm{Ei}(.)$ is the exponential integral function defined in ([18], Equation (8.211.1)). The integral part can be obtained by applying the Gauss–Chebyshev integral ([19], Equation (3.324.1)).

Moreover, defining $Z_3 = \gamma_{sr}^{x_2}$, we can obtain its CDF as

$$\begin{aligned}F_{Z_3}(z_3) &= \Pr\left(\gamma_{sr}^{x_2} < z_3\right) \\ &= 1 - e^{\frac{-z_3(\zeta\rho_{1,r}+1)}{(1-\beta)\rho_s(\alpha_2-\alpha_1 z_3)\varepsilon_{sr}}}.\end{aligned} \tag{27}$$

Based on (27), we can derive $\mathbb{E}\left[C_{sr}^{x_2}\right]$ as

$$\begin{aligned}\mathbb{E}\left[C_{sr}^{x_2}\right] &= \int_0^{\frac{\alpha_2}{\alpha_1}} \frac{1-F_{Z_3}(z_3)}{2(1+z_3)}dz_3 \\ &= \int_0^{\frac{\alpha_2}{\alpha_1}} \frac{e^{\frac{-z_3(\zeta\rho_{1,r}+1)}{(1-\beta)\rho_s(\alpha_2-\alpha_1 z_3)\varepsilon_{sr}}}}{2(1+z_3)}dz_3 \\ &= \frac{\pi}{2N}\sum_{n=1}^{N}\frac{\alpha_2\sqrt{1-z_n^2}}{2\alpha_1(1+z_n)}\times e^{\frac{-z_n(\zeta\rho_{1,r}+1)}{(1-\beta)\rho_s(\alpha_2-\alpha_1 z_n)\varepsilon_{sr}}}.\end{aligned} \tag{28}$$

The ESSR of wiretaping x_2 at E can be expressed as

$$\begin{aligned}\mathbb{E}\left[C_{e}^{x_2}\right] &= \frac{1}{2}\frac{1}{\rho_s\rho_{1,r}\varepsilon_{se}\varepsilon_{re}}\int_0^\infty\int_0^\infty \log\left(\frac{1+\frac{u_{se}}{u_{re}+1}}{1+\frac{\alpha_1 u_{se}}{1+u_{re}}}\right)e^{-\frac{u_{se}}{\rho_s\varepsilon_{se}}}e^{-\frac{u_{re}}{\rho_{1,r}\varepsilon_{re}}}du_{se}du_{re} \\ &= \frac{1}{2\rho_s\rho_{1,r}\varepsilon_{se}\varepsilon_{re}}\left[\int_0^\infty e^{-\frac{u_{re}}{\rho_{1,r}\varepsilon_{re}}}du_{re}\int_0^\infty \log\left(1+\frac{u_{se}}{u_{re}+1}\right)e^{-\frac{u_{se}}{\rho_s\varepsilon_{se}}}du_{se}\right. \\ &\quad \left. -\int_0^\infty e^{-\frac{u_{re}}{\rho_{1,r}\varepsilon_{re}}}du_{re}\int_0^\infty \log\left(1+\frac{\alpha_1 u_{se}}{u_{re}+1}\right)e^{-\frac{u_{se}}{\rho_s\varepsilon_{se}}}du_{se}\right] \\ &= \mathbb{E}\left[C_e^{x_1}\right]_{|\alpha_1=1} - \mathbb{E}\left[C_e^{x_1}\right].\end{aligned} \tag{29}$$

Substituting (25), (26), (28) and (29) into (23), the closed-form expression of ESSR can be derived as

$$
\begin{aligned}
C_{ssr,lb} \triangleq & \left\{ \frac{\pi}{2N} \sum_{n=1}^{N} \frac{\sqrt{1-z_n^2}}{2(1+z_n)} e^{\frac{-z_n(\zeta\rho_{1,r}+1)}{(1-\beta)\alpha_1\rho_s\varepsilon_{sr}}} \right. \\
& \left. - \frac{\pi^2}{2N\rho_{1,r}\varepsilon_{re}} e^{\frac{1}{\alpha_1\rho_s\varepsilon_{se}}} \sum_{n=1}^{N} \sqrt{1-z_n^2} e^{\frac{\tan\theta_n}{\alpha_1\rho_s\varepsilon_{se}} - \frac{\tan\theta_n}{\rho_{1,r}\varepsilon_{re}}} \mathrm{Ei}\left(-\frac{1+\tan\theta_n}{\alpha_1\rho_s\varepsilon_{se}}\right) \sec\theta_n^2 \right\}^+ \\
& + \left\{ \frac{\pi}{2N} \sum_{n=1}^{N} \frac{\alpha_2\sqrt{1-z_n^2}}{2\alpha_1(1+z_n)} e^{\frac{z_n}{(1-\beta)\rho_s(\alpha_2-\alpha_1 z_n)\varepsilon_{sr}}} - \mathbb{E}\left[C_e^{x_2}\right] \right\}^+ .
\end{aligned} \tag{30}
$$

The procedures of the proposed AN-aided secure transmission scheme are summarized as follows. In the first phase, the source transmits the superposed signal to the relay, which adopts a power splitting architecture for energy harvesting and information decoding. At the same time, the FD relay emits AN to the eavesdropper, and the two users keep silent. We assume that there is a worst-case eavesdropping at E, and E has decoded x_2 before starting to decode x_1. In the second phase, the source only transmits the energy symbol to the relay, and the relay employs DF protocol to forward the signal to the two NOMA users while conducting energy harvesting from the source. We evaluate the secrecy performance based on the ESSR metric and focus on the ESSR of the proposed AN-aided secrecy enhancing scheme. In particular, the lower bound of ESSR for cooperative NOMA transmission is calculated by using Jensen's inequality, as shown in (23). Then, according to (24) and (27), $\mathbb{E}\left[C_{sr}^{x_1}\right]$ and $\mathbb{E}\left[C_{sr}^{x_2}\right]$ can be obtained, respectively. Furthermore, $\mathbb{E}\left[C_e^{x_1}\right]$ and $\mathbb{E}\left[C_e^{x_2}\right]$ can be calculated based on (26) and (29), respectively. Finally, substituting $\mathbb{E}\left[C_{sr}^{x_1}\right]$, $\mathbb{E}\left[C_{sr}^{x_2}\right]$, $\mathbb{E}\left[C_e^{x_1}\right]$, and $\mathbb{E}\left[C_e^{x_2}\right]$ into (23), the lower bound of ESSR of the proposed AN-aided secure transmission scheme can be derived.

4. Simulations

In this section, we provide the numerical results of the proposed AN-aided secure transmission scheme to verify the correctness of the theoretical analysis in the previous section. Unless otherwise specified, the system parameters in the simulation are set as follows. The power allocation factors for the cooperative NOMA transmission are $\alpha_1 = 0.4$ and $\alpha_2 = 0.6$, respectively. The transmit power of the base station is $P_s = 10$ dBm, the noise power is $\sigma_i^2 = -40$ dBm, $\eta = 0.6$, and the Gauss–Chebyshev quadrature approximation is chosen as $N = 20$. Moreover, the average channel gain is set to $\varepsilon_i = 1$ ($i \in \{sr, ru_1, ru_2, se, re\}$).

To provide a comparative analysis of the proposed scheme, a benchmark scheme is considered in the simulation. The benchmark scheme is the conventional FD cooperative NOMA transmission scheme without AN. Following the same analytical method of the proposed scheme, the lower bound of ESSR of the benchmark scheme can be derived as

$$
\begin{aligned}
C_{ssr,lb}^{FD} \triangleq & \left\{ \frac{\pi}{2N} \sum_{n=1}^{N} \frac{\sqrt{1-z_n^2}}{2(1+z_n)} \mathrm{e}^{\frac{-z_n(\zeta\rho_r+1)}{(1-\beta)\alpha_1\rho_s\varepsilon_{sr}}} \mathrm{e}^{\frac{-z_n}{(1-\beta)\alpha_1\rho_s\varepsilon_{sr}}} - \frac{1}{2} e^{\frac{1}{\alpha_1\rho_s\varepsilon_{se}}} \mathrm{Ei}\left(-\frac{1}{\alpha_1\rho_s\varepsilon_{se}}\right) \right\}^+ \\
& + \left\{ \frac{\pi}{2N} \sum_{n=1}^{N} \frac{\alpha_1\sqrt{1-z_n^2}}{2\alpha_1+\alpha_2(1+z_n)} \mathrm{e}^{-\frac{(1+z_n)(\zeta\rho_r+1)}{(1-\beta)\rho_s\varepsilon_{sr}\alpha_1(1-z_n)}} \mathrm{e}^{-\frac{1+z_n}{\rho_s\varepsilon_{ru_1}\alpha_1(1-z_n)}} e^{-\frac{1+z_n}{2\alpha_1\rho_s\varepsilon_{ru_2}}} \right. \\
& \left. - \frac{\pi}{2N} \sum_{n=1}^{N} \frac{\alpha_1\sqrt{1-z_n^2}}{2\alpha_1+\alpha_2(1+z_n)} e^{-\frac{1+z_n}{\alpha_1\rho_s\varepsilon_{se}(1-z_n)}} \right\}^+ .
\end{aligned} \tag{31}
$$

From the derived theoretical formula, we can find that the eavesdropping rate of the conventional FD cooperative NOMA scheme without AN is much higher than that of our proposed scheme because there is no AN for disturbing the eavesdropper. For the proposed scheme, all of the power harvested by the relay in the first phase is exploited to generate a jamming signal, which significantly degrades the wiretapping capability of the eavesdropper. Therefore, our proposed scheme can achieve higher ESSR.

Figure 2 plots the ESSR versus different power allocation factor β. It can be obtained that for the proposed scheme, the optimal value of ESSR can be observed as β increasing. This is because the increase of β will lead to an improvement in the SI at the relay and enhance the AN emitted by the relay. SI has an inhibiting effect on ESSR, while the increment of AN reduces the eavesdropper's ability to improve ESSR. It can also be observed that by increasing the transmit power of the source, the ESSR performance of the system will become higher.

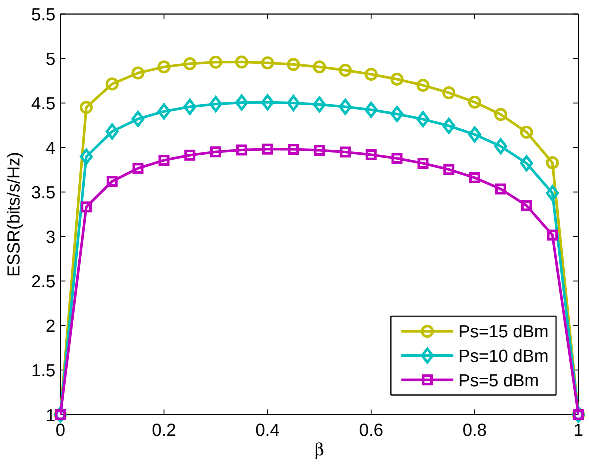

Figure 2. ESSR versus power allocation ratio β.

Figure 3 plots the theoretical analysis of the lower bound of ESSR and the simulation results versus the varying system transmit power P_s. Since the ESSR is affected by the power allocation factor β, the results under different power allocation factors are also provided. It can be seen that the simulation results match well with the approximated expression in (26), which is consistent with the results shown in Figure 2. The results prove the theoretical analysis of ESSR.

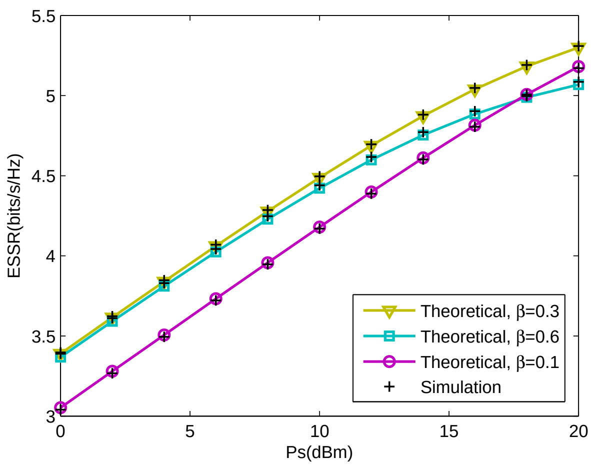

Figure 3. ESSR versus the whole transmit power P_s.

Figure 4 depicts the ESSR with different channel gain settings. Since the lower bound of ESSR is affected by the channel gain setting, we have five different channel gain settings. In case 1 and case 2, we have $\varepsilon_{sr} = 4$ and $\varepsilon_{re} = 4$, respectively. In case 3, all the channel gains are set to 1. In case 4 and case 5, $\varepsilon_{sr} = 0.4$ and $\varepsilon_{re} = 0.4$, respectively.

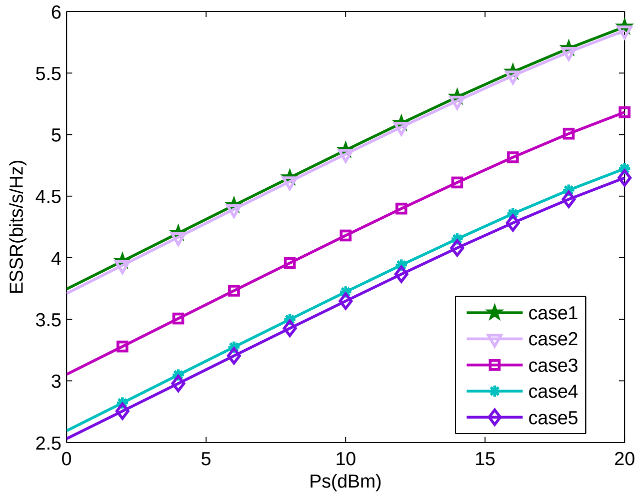

Figure 4. ESSR versus the whole transmit power P_s with different channel gains.

This is because as ε_{re} increases, the capability of the relay to perform cooperative jamming is enhanced. Therefore, the eavesdropping performance of E is reduced.

Figure 5 plots the ESSR versus the U_1's power allocation factor α_1. The ESSR of the system will improve as the U_1's power allocation factor decreases. The results show that there is a boost to ESSR when more power is allocated to the weak user.

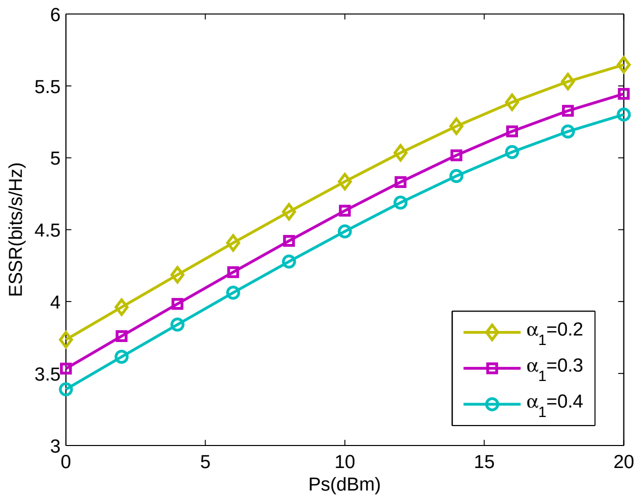

Figure 5. ESSR versus the whole transmit power P_s with different U_1's power allocation ratios α_1.

Figure 6 compares the ESSR of the proposed scheme with the conventional FD cooperative NOMA scheme without AN. It can be observed from the figure that our proposed scheme achieves higher ESSR than that of the conventional scheme over the whole range of the transmit power P_s, which indicates that the AN-aided transmission strategy employed at the FD relay can significantly improve the secrecy rate. Therefore, considering the worst-case assumption of the strong detection capability at the eavesdropper, AN is necessary for enhancing the secrecy rate performance of the source node in the wireless-powered, FD-relay-aided cooperative NOMA system.

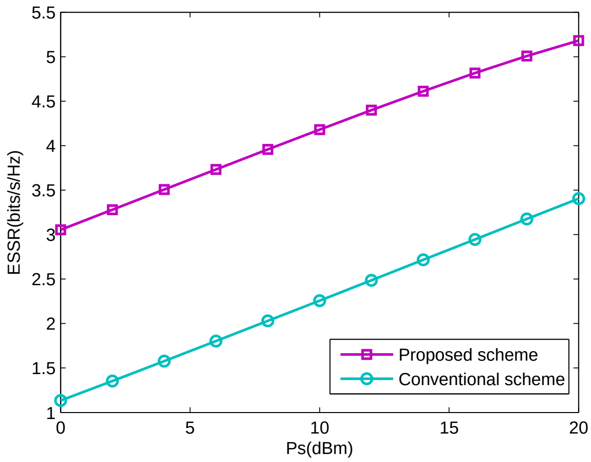

Figure 6. ESSR versus the whole transmit power P_s with different schemes.

5. Conclusions

This paper investigates the design of secrecy enhancing transmission strategy in cooperative NOMA systems with wireless-powered FD relaying. An AN-aided secure transmission scheme based on FD relaying is proposed to improve the secrecy performance of the system. From this work, the positive lower bound of ESSR is achieved, indicating that the perfect secrecy performance can be guaranteed, and a higher ESSR is obtained, compared to the conventional cooperative NOMA scheme. In modern wireless networks, our work can be applied to prevent the leakage of confidential information against eavesdroppers with strong eavesdropping capability, which attracts a lot of attention from both academia and industry. In the future, our aim is to extend this work to the multi-relay scenario, where the optimal relay is selected to forward the information signal, and the remaining relays can transmit AN to the eavesdropper.

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