Physical Layer Security Transmission Scheme Based on Artificial Noise in Cooperative SWIPT NOMA System

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RESEARCH

Physical Layer Security Transmission Scheme Based on Artificial Noise in Cooperative SWIPT NOMA System

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Abstract

Physical layer security of non-orthogonal multiple access (NOMA) system which uses simultaneous wireless information and power transfer (SWIPT) technique is deeply dicussed in this paper. Generally, eavesdropper in the downlink of NOMA system may use successive interference cancellation technology (SIC) to obtain the secrecy information of receiver. To tackle this problem, we propose a physical layer security scheme to minimize the transmit power of the base station (BS) while the secrecy rates of receivers are guaranteed. Moreover, semidefinite relaxation (SDR) method and successive convex approximation (SCA) technique are combined to solve above non-convex problem. Simulation results show that in comparison with other methods, our method can effectively reduce the transmit power of the BS.

Keywords: SWIPT; NOMA; power splitting (PS); secrecy communication; artificial noise (AN)

1 Introduction

High-speed transmission rates of smart terminals in fifth-generation (5G) wireless communication systems require vast spectrum resources [1, 2]. Traditional orthogonal mutiple access (OMA) approaches are difficult to meet the needs of high-speed, real-time and wide-bandwidth in 5G. Researchers proposed NOMA technique, one of the key technologies of 5G, to provide higher spectral efficiency (SE) of multiple users. Keypoint of NOMA is multiple non-orthogonal access of power domain. Thus, multiple users can to be served by the same resource block (time domain, frequency domain and code domain). However, due to mutual interference of non-orthogonal signal, the receiver has to use the SIC technique to extract desired information from received signal [3–5].

In addition, energy efficiency (EE) is another concern of 5G. Since radio frequency (RF) signals can carry information and transmit energy simultaneously, they can be used not only for information vehicle but also for energy collection of the system. At present, a technology which can effectively extend the service life of energy-limited device called SWIPT has been proposed [6]. Different from traditional energy harvesting (EH) technologies, such as solar and wind, SWIPT provides stable and controllable energy for wireless applications while transmitting the necessary information contained in RF signal. For this reason, there are many relevant studies on SWIPT has been appeared in the recent several years [7]. Specifically, Zhang proposed two practical receiver architectures to handle the technical limitations of existing circuit designs, namely, time-switching (TS) receiver and PS receiver [8]. Furthermore, Krikidis and Timotheou indicated that the PS technology achieves lower outage probability and higher gain than those of TS for applications with delay constraints [9].

Motivated by the requirements of 5G and the advantages of NOMA and SWIPT, using SWIPT to enhance SE and EE in NOMA system which contains energy-limited devices is a hotspot today [10]. Liu and Ding introduce SWIPT into NOMA system to extend self-sustaining time of system. This strategy employs the cell-center users as EH relays to improve communication quality of cell-edge users. Outage rates with respect to three kinds of relay selection schemes are evaluated in single-input single-output (SISO) scenario. The analytical results demonstrate that SWIPT technology can effectively enhance EE of conventional NOMA systems without jeopardizing its diversity gain [11]. Xu and Ding proposed a SWIPT NOMA cooperative transmission strategy to design joint beamformer and power-distribution in multi-input single-output (MISO) scene [12]. However, the security of cooperative transmission is not involved in their work. Thus, the private information is easily intercepted and eavesdropped from open wireless channel [13, 14]. Liu Y, etc. combined cooperative relay with interference technique to tackle this problem. Their research shows that their method can effectively improve the secrecy rate [15]. Zhou and Chu used AN technique to improve the information security of users in the SWIPT NOMA system which has an untrusted energy harvesting receiver [16]. However, the collaboration scheme of SWIPT and NOMA is not involved in their work. Thus, it motivates us to use AN-aided cooperative strategy to enhance physical-layer security of MISO SWIPT NOMA system. The main contributions of this paper are summarized as follows.

- We propose an AN-aided cooperative SWIPT NOMA strategy, where the cell-center user serves as an EH relay to help the cell-edge user to improve the secrecy rate. By applying the PS protocol, the cell-center user can simultaneously receive information and harvest energy used for the forwarding stage. In addition, multiple antennas and AN-aided techniques are exploited to protect the private information.
- The above scheme can be described as the minimum BS's transmit power subject to secrecy rate of each user. To tackle this problem, we need to jointly optimize beamforming vector, AN covariance matrix and PS ratio. Unfortunately, it is NP-hard. So, variable slack technique is combined with SCA method to get suboptimal solution of the original problem. The simulation results verify the effectiveness of the proposed scheme.

The paper is organized as follows. In Section 2, we first introduce the system model and the problem formulation of the cooperative SWIPT NOMA in MISO system. Next, an SCA-based iterative algorithm is proposed to solve the joint AN-aided beamforming design and power splitting control problem. Then, we present numerical results on the performance of different schemes in Section 3. Finally, we conclude the paper in Section 4.

Notations: Boldface capital letters and boldface lower case letters denote matrices and vectors, respectively. $\mathbb{C}$ represents the complex domain. $\mathbb{E}|\cdot|$ denotes the expectation operator. The superscript $(\cdot)^T$ and $(\cdot)^H$ denote the transpose and (Hermitian) conjugate transpose, respectively. $\mathrm{Tr}(\cdot)$ represents the trace of a matrix. $||\cdot||$

denotes the magnitude of a complex number. $\mathcal{CN}(\mathbf{0}, \mathbf{X})$ denotes the circularly symmetric complex Gaussian distribution with mean vector $\mathbf{0}$ and covariance matrix $\mathbf{X}$.

2 Methods/Experimental

2.1 System model and problem formulation

Consider a downlink in an MISO system as depicted in Fig. 1. BS is equipped with N_t antennas. Users and eavesdropper are equipped with a single antenna, respectively. Assume the channel quality of the user 2 and the eavesdropper better than that of user 1. For example, user 2 and eavesdropper are closer to the cell-center than user 1.

Cooperative SWIPT NOMA transmission scheme is divided into two phases. In the first phase, the eavesdropper intercepts the BS's transmit signal, and user 1 receives the BS's transmit signal while user 2 performs SWIPT to split the received signal into two parts, one for information decoding and the other for energy harvesting. In the second phase, user 2 uses harvested energy in phase 1 to forward the message received in phase 1 to user 1, while user 1 employs maximal-ratio combination (MRC) criterion to accumulate and decode the messages received in two phases. Detail of the process is presented next.

In the first transmission phase, in order to improve the security of the BS's transmit signal and reduce the risk of information leakage, an AN vector $\mathbf{v} \in \mathbb{C}^{N_t}$ is added to the transmit signal. Therefore, the transmit signal at the BS is described as $\mathbf{s} = \mathbf{w}_1 s_1 + \mathbf{w}_2 s_2 + \mathbf{v}$, where $s_1, s_2 \in \mathbb{C}$ are information bearing messages for user 1 and user 2, respectively. And $\mathbf{w}_1, \mathbf{w}_2 \in \mathbb{C}^{N_t}$ are the corresponding transmit beamformers. We assume that the power of the transmit symbol is normalized, i.e., $\mathbb{E}|s_1|^2 = \mathbb{E}|s_2|^2 = 1$, and the AN vector $\mathbf{v} \sim \mathcal{CN}(\mathbf{0}, \mathbf{S})$, where $\mathbf{S}$ is the covariance matrix of AN to be designed. Then, the signal received at user 1 is given by

$$y_1^{(1)} = \widetilde{\mathbf{h}}_1^H(\mathbf{w}_1 s_1 + \mathbf{w}_2 s_2 + \mathbf{v}) + n_1^{(1)}, \tag{1}$$

where $\widetilde{\mathbf{h}}_1^H \in \mathbb{C}^{N_t}$ is the channel impulse response vector between the BS and user 1, and $n_1^{(1)} \sim \mathcal{CN}(0, \sigma_1^2)$ represents the additive Gaussian white noise (AWGN) at user 1. Then, the signal-to-interference-plus-noise-ratio (SINR) received by user 1 for s_1 can be expressed as

$$\mathrm{SINR}_1^{(1)} = \frac{|\widetilde{\mathbf{h}}_1^H \mathbf{w}_1|^2}{|\widetilde{\mathbf{h}}_1^H \mathbf{w}_2|^2 + |\widetilde{\mathbf{h}}_1^H \mathbf{v}|^2 + \sigma_1^2}, \tag{2}$$

by defining $\mathbf{h}_1 = \widetilde{\mathbf{h}}_1/\sigma_1$, (2) is transformed as

$$\mathrm{SINR}_1^{(1)} = \frac{\mathbf{h}_1^H \mathbf{w}_1 \mathbf{w}_1^H \mathbf{h}_1}{\mathbf{h}_1^H(\mathbf{w}_2\mathbf{w}_2^H + \mathbf{S})\mathbf{h}_1 + 1}. \tag{3}$$

As shown in Fig. 2, the power splitting architecture with respect to user 2, is introduced to perform SWIPT. Hence, the received signal for information decoding at user 2 can be described as

$$y_2^{(1)} = \sqrt{1-\rho}\,\widetilde{\mathbf{h}}_2^H(\mathbf{w}_1 s_1 + \mathbf{w}_2 s_2 + \mathbf{v}) + n_2^{(1)}, \tag{4}$$

where $\rho \in [0,1]$ is the PS ratio of energy harvesting to be optimized later, $\widetilde{\mathbf{h}}_2^H \in \mathbb{C}^{N_t}$ is the channel impulse response vector between the BS and user 2, $n_2^{(1)} \sim \mathcal{CN}(0,\sigma_2^2)$ represents the AWGN.

According to the NOMA principle, SIC is performed at user 2. Specifically, user 2 first decodes user 1's message (i.e., s_1) and then subtracts this message from the received signal to decode its own message [17]. Therefore, the SINR received at user 2 for s_1 can be expressed as

$$\mathrm{SINR}_{2,s_1}^{(1)} = \frac{(1-\rho)\mathbf{h}_2^H \mathbf{w}_1 \mathbf{w}_1^H \mathbf{h}_2}{(1-\rho)\mathbf{h}_2^H (\mathbf{w}_2 \mathbf{w}_2^H + \mathbf{S})\mathbf{h}_2 + 1}, \tag{5}$$

where $\mathbf{h}_2 = \widetilde{\mathbf{h}}_2/\sigma_2$.

Then, user 2 subtracts s_1 from $y_2^{(1)}$ to further decode its own message s_2. The corresponding SINR can be described as

$$\mathrm{SINR}_{2,s_2}^{(1)} = \frac{(1-\rho)\mathbf{h}_2^H \mathbf{w}_2 \mathbf{w}_2^H \mathbf{h}_2}{(1-\rho)\mathbf{h}_2^H \mathbf{S}\mathbf{h}_2 + 1}. \tag{6}$$

On the other hand, the energy harvested by user 2 is modeled as [18]

$$E = \rho(|\widetilde{\mathbf{h}}_2^H \mathbf{w}_1|^2 + |\widetilde{\mathbf{h}}_2^H \mathbf{w}_2|^2 + |\widetilde{\mathbf{h}}_2^H \mathbf{v}|^2)\eta, \tag{7}$$

where η is the ratio of the first phase in a transmission time slot, and we assume that the two phases have the same transmission duration, then $\eta = 0.5$.

Thus, in the second phase, the transmit power of user 2 related to forwarding messages is

$$P_t = \frac{E}{1-\eta} = \rho(|\widetilde{\mathbf{h}}_2^H \mathbf{w}_1|^2 + |\widetilde{\mathbf{h}}_2^H \mathbf{w}_2|^2 + |\widetilde{\mathbf{h}}_2^H \mathbf{v}|^2). \tag{8}$$

In addition, the signal received at the eavesdropper can be expressed as

$$y_e^{(1)} = \widetilde{\mathbf{f}}^H(\mathbf{w}_1 s_1 + \mathbf{w}_2 s_2 + \mathbf{v}) + n_e^{(1)}, \tag{9}$$

where $\widetilde{\mathbf{f}}^H \in \mathbb{C}^{N_t}$ is the channel impulse response vector between the BS and eavesdropper, and $n_e^{(1)} \sim \mathcal{CN}(0,\sigma_e^2)$ represents the AWGN at eavesdropper. Then, the SINR received by eavesdropper for s_1 can be expressed as

$$\mathrm{SINR}_{e,s_1}^{(1)} = \frac{\mathbf{f}^H \mathbf{w}_1 \mathbf{w}_1^H \mathbf{f}}{\mathbf{f}^H(\mathbf{w}_2 \mathbf{w}_2^H + \mathbf{S})\mathbf{f} + 1}. \tag{10}$$

where $\mathbf{f} = \widetilde{\mathbf{f}}/\sigma_e$.

The eavesdropper then performs the SIC, subtracts s_1 from its signal to further decode the other message s_2. The corresponding SINR can be described as

$$\mathrm{SINR}_{e,s_2}^{(1)} = \frac{\mathbf{f}^H \mathbf{w}_2 \mathbf{w}_2^H \mathbf{f}}{\mathbf{f}^H \mathbf{S}\mathbf{f} + 1}. \tag{11}$$

In the second phase, user 2 forwards the message to user 1 with the harvested energy. At this point, the signal received at user 1 is

$$y_1^{(2)} = \sqrt{P_t} g_1 s_1 + n_1^{(2)}, \tag{12}$$

where $g_1 \in \mathbb{C}$ is the channel coefficient from user 2 to user 1, and $n_1^{(2)} \sim \mathcal{CN}(0, \sigma_1^2)$ is the AWGN at user 1. Note that we consider the case of $\sigma_1^2 = \sigma_2^2$ for the simplicity of exposition. Thus, the SNR received by user 1 for s_1 can be given by

$$\mathrm{SNR}_{1,s_1}^{(2)} = \rho g \left(\mathbf{h}_2^H (\mathbf{w}_1 \mathbf{w}_1^H + \mathbf{w}_2 \mathbf{w}_2^H + \mathbf{S}) \mathbf{h}_2 \right), \tag{13}$$

where $g = |g_1|^2$.

At the end of phase 2, the user 1 employs the signals received from the BS and the user 2 to jointly decodes the message by using the MRC. Hence the equivalent SINR at user 1 can be written as

$$\begin{aligned} \mathrm{SINR}_{1,s_1} &= \mathrm{SINR}_1^{(1)} + \mathrm{SNR}_{1,s_1}^{(2)} \\ &= \frac{\mathbf{h}_1^H \mathbf{w}_1 \mathbf{w}_1^H \mathbf{h}_1}{\mathbf{h}_1^H (\mathbf{w}_2 \mathbf{w}_2^H + \mathbf{S}) \mathbf{h}_1 + 1} + \rho g \left(\mathbf{h}_2^H (\mathbf{w}_1 \mathbf{w}_1^H + \mathbf{w}_2 \mathbf{w}_2^H + \mathbf{S}) \mathbf{h}_2 \right). \end{aligned} \tag{14}$$

Therefore, according to the SINR of the legitimate user and the eavesdropper, the secrecy rate R_1 and secrecy rate R_2 of the user 1 and the user 2 are defined as follows

$$R_1 = \min \left\{ \log_2(1 + \mathrm{SINR}_{1,s_1}), \log_2(1 + \mathrm{SINR}_{2,s_1}^{(1)}) \right\} - \log_2(1 + \mathrm{SINR}_{e,s_1}^{(1)}) \tag{15a}$$

$$R_2 = \log_2(1 + \mathrm{SINR}_{2,s_2}^{(1)}) - \log_2(1 + \mathrm{SINR}_{e,s_2}^{(1)}). \tag{15b}$$

we want to minimize the transmit power of the BS while guaranteeing the level of secrecy rates related to users. The optimization problem can be expressed as follow

$$\begin{aligned} \mathbf{P}_1 : \min_{\rho, \mathbf{w}_1, \mathbf{w}_2, \mathbf{S}} \quad & \mathrm{Tr}(\mathbf{w}_1 \mathbf{w}_1^{\mathrm{H}} + \mathbf{w}_2 \mathbf{w}_2^{\mathrm{H}} + \mathbf{S}) & \text{(16a)} \\ \text{s.t.} \quad & C0 : R_1 \geq \gamma_1, & \text{(16b)} \\ & C1 : R_2 \geq \gamma_2, & \text{(16c)} \\ & C2 : 0 \leq \rho < 1, & \text{(16d)} \\ & C3 : \mathbf{S} \succeq 0, & \text{(16e)} \end{aligned}$$

where γ_1 and γ_2 represent the minimum required secret rate thresholds with respect to user 1 and user 2, respectively. The constraint $C0$ can guarantee the secure transmission of message s_1 at user 1 and user 2, and the constraint $C1$ ensures the secure transmission of message s_2 at user 2. Observing equ (15.a) and equ (15.b), we can find that ρ, $\mathbf{w}_1$ and $\mathbf{w}_2$ are coupled together in the R_1 and R_2. Thus, P1 is a nonconvex problem and is difficult to solve. In the following, we will firstly employ SDR technique to reformulate P1 and then approximately solve the reformulated problem with an SCA-based iterative algorithm.

$$R_{1,s_1} = \frac{\left[\mathrm{Tr}\left((\mathbf{W}_1+\mathbf{W}_2+\mathbf{S})\mathbf{F}\right)+1\right]}{\left\{\frac{\left[\mathrm{Tr}\left((\mathbf{W}_1+\mathbf{W}_2+\mathbf{S})\mathbf{H}_1\right)+1\right]}{\left[\mathrm{Tr}\left((\mathbf{W}_2+\mathbf{S})\mathbf{H}_2\right)+1\right]}+\rho g \mathrm{Tr}\left((\mathbf{W}_1+\mathbf{W}_2+\mathbf{S})\mathbf{H}_2\right)\right\}\left[\mathrm{Tr}\left((\mathbf{W}_2+\mathbf{S})\mathbf{F}\right)+1\right]}$$
$$R_{2,s_1} = \frac{\left[(1-\rho)\mathrm{Tr}\left((\mathbf{W}_2+\mathbf{S})\mathbf{H}_2\right)+1\right]\left[\mathrm{Tr}\left((\mathbf{W}_1+\mathbf{W}_2+\mathbf{S})\mathbf{F}\right)+1\right]}{\left[(1-\rho)\mathrm{Tr}\left((\mathbf{W}_1+\mathbf{W}_2+\mathbf{S})\mathbf{H}_2\right)+1\right]\left[\mathrm{Tr}\left((\mathbf{W}_2+\mathbf{S})\mathbf{F}\right)+1\right]}$$
$$R_{2,s_2} = \frac{\left[(1-\rho)\mathrm{Tr}\left(\mathbf{S}\mathbf{H}_2\right)+1\right]\left[\mathrm{Tr}\left((\mathbf{W}_2+\mathbf{S})\mathbf{F}\right)+1\right]}{\left[(1-\rho)\mathrm{Tr}\left((\mathbf{W}_2+\mathbf{S})\mathbf{H}_2\right)+1\right]\left[\mathrm{Tr}\left(\mathbf{S}\mathbf{F}\right)+1\right]} \tag{17}$$

2.2 AN-aided Beamforming Design and Power Splitting Control

Let $\mathbf{W}_1 = \mathbf{w}_1\mathbf{w}_1^H$, $\mathbf{W}_2 = \mathbf{w}_2\mathbf{w}_2^H$ and drop rank-one constraints rank$(\mathbf{W}_1) = 1$, rank$(\mathbf{W}_2) = 1$. P1 can be relaxed to P2, given as

$$\mathbf{P}_2 : \min_{\rho,\mathbf{W}_1,\mathbf{W}_2,\mathbf{S}} \mathrm{Tr}(\mathbf{W}_1+\mathbf{W}_2+\mathbf{S}) \tag{18a}$$
$$\text{s.t.} \quad C4 : R_{1,s_1} \leqslant 2^{-\gamma_1}, \tag{18b}$$
$$C5 : R_{2,s_1} \leqslant 2^{-\gamma_1}, \tag{18c}$$
$$C6 : R_{2,s_2} \leqslant 2^{-\gamma_2}, \tag{18d}$$
$$C7 : 0 \leq \rho < 1, \tag{18e}$$
$$C8 : \mathbf{S} \succeq 0, \mathbf{W}_1 \succeq 0, \mathbf{W}_2 \succeq 0, \tag{18f}$$

where $\mathbf{H}_1 \triangleq \mathbf{h}_1\mathbf{h}_1^H$, $\mathbf{H}_2 \triangleq \mathbf{h}_2\mathbf{h}_2^H$ and $\mathbf{F} \triangleq \mathbf{f}\mathbf{f}^H$. Moreover, R_{1,s_1} and R_{2,s_1} represent the secrecy rates of message s_1 at user 1 and user 2, respectively. R_{2,s_2} represents that of message s_2 at user 2(c.f. (17)). Due to the constraints $C4$, $C5$ and $C6$ are still non-convex, they are converted to the following equivalent by introducing exponential auxiliary variables [19]. The constraint $C4$ is equivalently expressed as

$$\exp\left(x_1-y_1-y_2\right) \leqslant 2^{-\gamma_1}, \tag{19a}$$
$$\mathrm{Tr}\left((\mathbf{W}_1+\mathbf{W}_2+\mathbf{S})\mathbf{F}\right)+1 \leqslant \exp(x_1), \tag{19b}$$
$$\frac{\left[\mathrm{Tr}\left((\mathbf{W}_1+\mathbf{W}_2+\mathbf{S})\mathbf{H}_1\right)+1\right]}{\left[\mathrm{Tr}\left((\mathbf{W}_2+\mathbf{S})\mathbf{H}_1\right)+1\right]}+\rho g\mathrm{Tr}\left((\mathbf{W}_1+\mathbf{W}_2+\mathbf{S})\mathbf{H}_2\right) \geqslant \exp(y_1), \tag{19c}$$
$$\mathrm{Tr}\left((\mathbf{W}_2+\mathbf{S})\mathbf{F}\right)+1 \geqslant \exp(y_2), \tag{19d}$$

where x_1, y_1, y_2 are exponential auxiliary variables. Here, only (19b) and (19c) remain as non-convex constraints. By using the first-order Taylor expansion approximation, the non-convex constraint (19b) can be approximated as

$$\mathrm{Tr}\left((\mathbf{W}_1+\mathbf{W}_2+\mathbf{S})\mathbf{F}\right)+1 \leqslant \exp(\widetilde{x_1})(x_1-\widetilde{x_1}+1), \tag{20}$$

where $\widetilde{x}_1$ is an approximate value, and it is equal to x_1, when the corresponding constraints are tight.

Furthermore, by introducing an auxiliary variable $x_2 \geqslant 0$, the constraint (19c) can be equivalently expressed as

$$\mathrm{Tr}\left((\mathbf{W}_1+\mathbf{W}_2+\mathbf{S})\mathbf{H}_1\right) \geqslant \mathrm{x}_2\mathrm{Tr}\left((\mathbf{W}_2+\mathbf{S})\mathbf{H}_1\right)+x_2-1, \tag{21a}$$
$$\rho g\mathrm{Tr}\left((\mathbf{W}_1+\mathbf{W}_2+\mathbf{S})\mathbf{H}_2\right) \geqslant \exp(y_1)-x_2. \tag{21b}$$

For constraint (21a), an approximate convex constraint is produced by using the arithmetic-geometric mean (AGM) inequality $xy \leqslant z$. That is, for any non-negative variable x, y and z, if and only if $a = \sqrt{y/x}$, the following formula holds

$$2xy \leqslant (ax)^2 + (y/a)^2 \leqslant 2z. \tag{22}$$

Therefore, the constraint (21a) is approximated by a convex constraint as follows

$$\left(\widetilde{a}_1 x_2\right)^2 + \left(\mathrm{Tr}\left((\mathbf{W}_2 + \mathbf{S})\mathbf{H}_1\right)/\widetilde{\mathrm{a}}_1\right)^2 \leqslant 2\mathrm{Tr}\left((\mathbf{W}_1 + \mathbf{W}_2 + \mathbf{S})\mathbf{H}_1\right) + 2 - 2x_2, \tag{23}$$

where $\widetilde{a}_1$ is an approximate value, which is updated after each iteration by the following formula

$$\widetilde{a}_1 = \sqrt{\mathrm{Tr}\left((\mathbf{W}_2 + \mathbf{S})\mathbf{H}_1\right)/x_2}. \tag{24}$$

Using epigraph reformulation [20], the constraint (21b) can be transformed into a non-convex quadratic constraint and a convex LMI constraint as below

$$u^2 \geqslant \exp(y_1) - x_2, \tag{25a}$$

$$\begin{bmatrix} g\rho & u \\ u & \mathrm{Tr}\left((\mathbf{W}_1 + \mathbf{W}_2 + \mathbf{S})\mathbf{H}_2\right) \end{bmatrix} \succeq 0. \tag{25b}$$

And then, the non-convex quadratic inequality constraint (25a) is still approximated by Taylor expansion as

$$2\widetilde{u}u - \widetilde{u}^2 \geqslant \exp(y_1) - x_2, \tag{26}$$

where $\widetilde{u}$ is an approximate value.

Similar to $C4$, constraint $C5$ is approximated as

$$\exp\left(x_3 + x_4 - y_3 - y_4\right) \leqslant 2^{-\gamma_1}, \tag{27a}$$

$$\left(\widetilde{a}_2(1-\rho)\right)^2 + \left(\mathrm{Tr}\left((\mathbf{W}_2 + \mathbf{S})\mathbf{H}_2\right)/\widetilde{\mathrm{a}}_2\right)^2 \leqslant 2\exp(\widetilde{x}_3)(x_3 - \widetilde{x}_3 + 1) - 2, \tag{27b}$$

$$\mathrm{Tr}\left((\mathbf{W}_1 + \mathbf{W}_2 + \mathbf{S})\mathbf{F}\right) + 1 \leqslant \exp(\widetilde{x}_4)(x_4 - \widetilde{x}_4 + 1), \tag{27c}$$

$$2\widetilde{t}t - \widetilde{t}^2 + 1 \geqslant \exp(y_3), \tag{27d}$$

$$\begin{bmatrix} 1-\rho & t \\ t & \mathrm{Tr}\left((\mathbf{W}_1 + \mathbf{W}_2 + \mathbf{S})\mathbf{H}_2\right) \end{bmatrix} \succeq 0, \tag{27e}$$

$$\mathrm{Tr}\left((\mathbf{W}_2 + \mathbf{S})\mathbf{F}\right) + 1 \geqslant \exp(y_4). \tag{27f}$$

where $\widetilde{x}_3$, $\widetilde{x}_4$, $\widetilde{t}$ and $\widetilde{a}_2$ are approximate values. In addition, $\widetilde{a}_2$ is updated after each iteration by the following formula

$$\widetilde{a}_2 = \sqrt{\mathrm{Tr}\left((\mathbf{W}_2 + \mathbf{S})\mathbf{H}_2\right)/(1-\rho)} \tag{28}$$

Similar to $C5$, constraint $C6$ is approximated as

$$\exp\left(x_5 + x_6 - y_5 - y_6\right) \leqslant 2^{-\gamma_2}, \tag{29a}$$
$$\left(\widetilde{a}_3(1-\rho)\right)^2 + \left(\mathrm{Tr}\left(\mathbf{SH}_2\right)/\widetilde{\mathrm{a}}_3\right)^2 \leqslant 2\exp(\widetilde{x}_5)(x_5 - \widetilde{x}_5 + 1) - 2, \tag{29b}$$
$$\mathrm{Tr}\left((\mathbf{W}_2 + \mathbf{S})\mathbf{F}\right) + 1 \leqslant \exp(\widetilde{x}_6)(x_6 - \widetilde{x}_6 + 1), \tag{29c}$$
$$2\widetilde{q}q - \widetilde{q}^2 + 1 \geqslant \exp(y_5), \tag{29d}$$
$$\begin{bmatrix} 1-\rho & q \\ q & \mathrm{Tr}\left((\mathbf{W}_2 + \mathbf{S})\mathbf{H}_2\right) \end{bmatrix} \succeq 0, \tag{29e}$$
$$\mathrm{Tr}\left(\mathbf{SF}\right) + 1 \geqslant \exp(\mathrm{y}_6). \tag{29f}$$

where $\widetilde{x}_5$, $\widetilde{x}_6$, $\widetilde{q}$ and $\widetilde{a}_3$ are approximate values. Moreover, $\widetilde{a}_3$ is updated after each iteration by the following formula

$$\widetilde{a}_3 = \sqrt{\mathrm{Tr}\left(\mathbf{SH}_2\right)/(1-\rho)}. \tag{30}$$

Therefore, P2 can be approximated as P3 as follows

$$\begin{aligned} \mathbf{P}_3 : \min_{\rho, \mathbf{W}_1, \mathbf{W}_2, \mathbf{S}, x_i, y_i, u, t, q} \ & \mathrm{Tr}(\mathbf{W}_1 + \mathbf{W}_2 + \mathbf{S}) \\ \text{s.t.}(18\text{e}), (18\text{f})(19\text{a}), (19\text{d}), (20), (23), (25\text{b}), (26), (27), (29) \end{aligned} \tag{31}$$

where $i \in \{1,2,3,4,5,6\}$. We can see that P3 is a standard convex optimization problem. According to the solution of P3, an iterative algorithm using SCA can be developed to solve P1, the specific solution process is shown in Table 1. In adiition, if the solution $(\mathbf{W}_1^*, \mathbf{W}_2^*)$ yielded by SDR is rank-one, then the optimal beamforming vectors $\mathbf{w}_1^*$ and $\mathbf{w}_2^*$ are obtained by eigenvalue-decomposition of $\mathbf{W}_1^*$ and $\mathbf{W}_2^*$, respectively. Otherwise, the suboptimal solution can be yielded by using Gaussian randomization procedure [21].

Table 1 the SCA-based algorithm

Algorithm 1 SCA Method for Solving P1

1: **Setting:**
  Secrecy rate threshold γ_1 and γ_2,and the tolerance error ξ;
2: **Initialization:**
  The iterative number $n = 1$, transmit power $P_{opt}^{(n)}$,
  approximate values $\widetilde{x}_i^{(n)}$, $\widetilde{a}^{(n)}$, $\widetilde{u}^{(n)}$, $\widetilde{t}^{(n)}$ and $\widetilde{q}^{(n)}$;
3: **Repeat:**
  Using CVX solver to solve P3 for the given approximate values;
  obtain $\widetilde{x}_i^{(n+1)}$, $\widetilde{a}^{(n+1)}$, $\widetilde{u}^{(n+1)}$, $\widetilde{t}^{(n+1)}$ and $\widetilde{q}^{(n+1)}$;
  update the iterative number $n = n + 1$;
  calculate the total transmit power $P_{opt}^{(n+1)}$;
  if $\left|P_{opt}^{(n+1)} - P_{opt}^{(n)}\right| \leqslant \xi$
    break;
  end;
4: **Output:**
  PS ratio ρ, beamformers $\mathbf{W}_1$ and $\mathbf{W}_2$, AN covariance matrix $\mathbf{S}$.

3 Results and Discussion

In this section, some simulation results are shown to demonstrate the performance of the proposed AN-aided cooperate SWIPT NOMA transmission scheme. Consider two legitimate users and an eavesdropper randomly allocated in an $5m \times 6m$ area, and the BS is fixed at the edge with a coordinate $(0m, 2.5m)$. The distance-dependent path loss is modeled by $P_L = 10^{-3}d^{-\alpha}$, in which d and α denote the Euclidean distance and path loss exponent, respectively. Using the Racian fading channel model, the downlink channels are modeled as

$$
\begin{aligned}
\widetilde{\mathbf{h}}_2 &= \sqrt{\frac{K}{1+K}}\mathbf{h}_2^{\mathrm{LOS}} + \sqrt{\frac{1}{1+K}}\mathbf{h}_2^{\mathrm{NLOS}} \\
\widetilde{\mathbf{f}} &= \sqrt{\frac{K}{1+K}}\mathbf{f}^{\mathrm{LOS}} + \sqrt{\frac{1}{1+K}}\mathbf{f}^{\mathrm{NLOS}} \\
g_1 &= \sqrt{\frac{K}{1+K}}g_1^{\mathrm{LOS}} + \sqrt{\frac{1}{1+K}}g_1^{\mathrm{NLOS}}
\end{aligned}
$$

where K denotes the Rician factor, $\mathbf{h}_2^{\mathrm{LOS}}$, $\mathbf{f}^{\mathrm{LOS}}$ and g_1^{LOS} are the line-of-sight (LOS) deterministic components, $\mathbf{h}_2^{\mathrm{NLOS}}$, $\mathbf{f}^{\mathrm{NLOS}}$ and g_1^{NLOS} are the Rayleigh fading components. The detailed simulation parameters are given in Table 2.

Table 2 Simulation parameters

Parameters	Notation	Typical Values
Numbers of antennas	N_t	2
Variances of noise at user 1	σ_1^2	-60dBm
Variances of noise at user 2	σ_2^2	-60dBm
Variances of noise at eavesdropper	σ_e^2	-60dBm
Path loss exponent of user 1	α_1	4
Path loss exponent of user 2	α_2	2
Path loss exponent of eavesdropper	α_e	3
Rician factor	K	3
Channel distribution	$\widetilde{\mathbf{h}}_1$	$\mathcal{CN}(\mathbf{0}, 2\mathbf{I})$
	$\mathbf{h}_2^{\mathsf{NLOS}}$	$\mathcal{CN}(\mathbf{0}, \mathbf{I})$
	$\mathbf{f}^{\mathsf{NLOS}}$	$\mathcal{CN}(\mathbf{0}, \mathbf{I})$
	g_1^{NLOS}	$\mathcal{CN}(\mathbf{0}, \mathbf{I})$

We introduce some other transmission strategies, namely the AN-aided NOMA strategy, Non-AN SWIPT NOMA strategy and AN-aided time division mutiple access (TDMA) strategy.

- In the AN-aided NOMA strategy, the system still performs the NOMA strategy. However, SWIPT is not executed at user 2, i.e., the cooperative transmission stage is removed in the system. So, in this strategy, power splitting is not to be considered.
- In the Non-AN SWIPT NOMA strategy, we do not add an AN to the BS's transmit signal in the system. Therefore, AN covariance matrix optimizing is not to be considered in this strategy.
- In the AN-aided TDMA strategy, the system performs the TDMA (time division multiple access) mode, i.e., the BS transmits information to user 1 or user 2 at different dynamic time intervals.

Fig. 3 shows minimum transmission power of the BS with respect to the number iterations of proposed algorithm. The minimum required secrecy rate of user 1 is set to be 0.5 Bits/s/Hz. The minimum required secrecy rate of user 2 is set to be 0.3 Bits/s/Hz, 0.5 Bits/s/Hz or 0.7 Bits/s/Hz, respectively. It can be found that only few iterations are required to achieve the minimum transmission power of the BS in all case, which indicates that proposed algorithm is effective.

Fig. 4 shows minimum transmission power of the BS with respect to secrecy rate of user 1 and secrecy rate of user 2, respectively. It can be found that in the all case, NOMA transmission strategies are superior to the TDMA transmission strategy, indicating the advantage of NOMA in improving the system SE. Moreover, our strategy obtains smaller transmission power of the BS than that of other NOMA strategies.

Since user 1 locating at the edge of the cell while user 2 locating at the center of the cell, their secrecy rates have different impact on transmission power. Firstly, we analyze the influence of user 1's secrecy rate on transmission power when the secrecy rate of user 2 was fixed. Again, we analyze the influence of user 2's secrecy rate on transmission power when the secrecy rate of user 1 was fixed.

Fig. 5 shows the minimum transmission power of the BS versus the secrecy rate of user 1, where the secrecy rate of user 2 is fixed by 0.5 Bits/s/Hz. Compared with that of other transmission strategies, the transmission power of the proposed AN-aided SWIPT NOMA strategy is the lowest, which demonstrates that the collaboration between SWIPT and NOMA is effective. In addition, it also can be seen that the gap between the Non-AN SWIPT NOMA transmission strategy and the proposed strategy broaden gradually with increasing of the user 1's secrecy rate, which indicates that using AN-aided to protect the private information is feasible in a SWIPT NOMA system.

Fig. 6 shows the minimum transmission power of the BS versus the secrecy rate of user 2, where the secrecy rate of user 1 is fixed by 0.5 Bits/s/Hz. We observe that the curves of the three NOMA transmission strategies are more smooth than that of TDMA transmission strategy. This indicates that the NOMA transmission strategies are robust with respect to the cell-center user rate, i.e., under the same transmit power constraint and cell-edge user secrecy rate, the NOMA can significantly increase the secrecy rate of the cell-center user compared to that of TDMA. On the other hand, we find that gap of transmission power between AN-aided SWIPT NOMA strategy and AN-aided NOMA strategy decrease gradually with increasing of secrecy rate requirement. Moreover, gap of transmission power between AN-aided and Non-AN strategies decreases gradually with increasing of the secrecy rate. It clearly demonstrates that gain of user in cell-center caused by SWIPT-cooperative and AN-aided techniques decrease gradually with the increasing of secrecy rate.

Table 3 Relationship among PS ratio, secrecy rate of user 1, secrecy rate of user 2

ρ \ $\gamma 2$ / $\gamma 1$	0.1	0.3	0.5	0.7	0.9
0.1	0.5592	0.4014	0.2546	0.1120	0.0077
0.3	0.6417	0.4988	0.3693	0.2387	0.0866
0.5	0.6897	0.5563	0.4381	0.3186	0.1916
0.7	0.7208	0.5943	0.4840	0.3727	0.2521
0.9	0.7468	0.6208	0.5161	0.4110	0.2954

Table 3 shows the relationship among the PS ratio, the secrecy rate of user 1 and the secrecy rate of user 2. It can be seen that the PS ratio decreases sharply with the user 2's secrecy rate increasing, but increases slowly with the user 1's secrecy rate increasing. This is because the power related to the information decoding of the user 2 is completely determined only by $1-\rho$. Higher secrecy rate requirement of user 2, more power needs to be allocated. Different from that of user 2, the secrecy rate of user 1 is determined by two parts (the transmission signal of the BS and user 2), and thus is less sensitive to the PS ratio than that of user 2.

4 Conclusions

To promote the physical-layer security of the downlink in the MISO system, we propose an AN-aided cooperate SWIPT NOMA strategy. In the scene of one SIC-capable eavesdropper, we explore a cooperative transmission scheme based on multi-antenna, AN-aided, and PS techniques to minimize transmit power of the BS while satisfying secrecy rate of all legitimate users. This NP-hard problem needs to joint optimize the beamforming vector of multi-antenna, the covariance matrix of AN-aided and the PS ratio. Thus, we design a suboptimal algorithm by using SDR and SCA techniques to tackle above NP-hard problem, Simulation studies verify the effectiveness of the proposed transmission scheme.

Abbreviations

NOMA: non-orthogonal mutiple access; SWIPT: simultaneous wireless information and power transfer; SIC: successive interference cancellation; BS: base station; SDR: semidefinite relaxation; SCA: successive convex approximation; PS: power splitting; AN: artificial noise; 5G: fifth-generation; OMA: orthogonal mutiple access; SE: spectral efficiency; EE: energy efficiency; RF: redio frequency; EH: energy harvesting; TS: time-switching; SISO: single-input single-output; MISO: mutiple-input single-output; MRC: maximal-retio combination; AWGN: additive Gaussian white noise; SINR: signal-to-interference-noise-ratio; LOS: line-of-sight; TDMA: time division mutiple accesss.

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Availability of data and materials

Data sharing not applicable to this paper since no datasets were analyzed during current study.

Competing interests

The authors declare that they have no competing interests.

Consent for publication

Not applicable.

Authors' contributions

Y.J is the main author of the current article. Y.J was responsible for investigating the AN-aided beamforming design and power splitting control method that are suitable to be implemented. Z.H conceived, designed the study and drafted the manuscript. D.X participated in the design of the study and helped to draft the manuscript and revised it critically. All authors read and approved the final manuscript.

Authors' information

Not applicable.

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References

1. Z.Wei, D.N, J.Yuan, H.Wang: Optimal resource allocation for power-efficient MC-NOMA with imperfect channel state information. IEEE Transactions on Communications **65**(9), 3944–3961 (2017)
2. F.Zhou, N.C.Beaulieu, Z.Li, J.Si, P.Qi: Energy-efficient optimal power allocation for fading cognitive radio channels: Ergodic capacity, outage capacity, and minimum-rate capacity. IEEE Transactions on Wireless Communications **15**(4), 2741–2755 (2016)
3. D.Tse, P.Viswannath: Fundamentals of Wireless Communication, (2005)
4. Z.Ding, Z.Yang, P.Fan, H.V.Poor: On the performance of non-orthogonal multiple access in 5G systems with randomly deployed users. IEEE signal processing letters **21**(12), 1501–1505 (2014)
5. Z.Ding, P.Fan, H.V.Poor: Impact of user pairing on 5G nonorthogonal multiple-access downlink transmissions. IEEE Transactions on Vehicular Technology **65**(8), 6010–6023 (2016)
6. Z.Zhu, Z.Chu, Z.Wang, L.Lee: Outage constrained robust beamforming for secure broadcasting systems with energy harvesting. IEEE Transactions on Wireless Communications **15**(11), 7610–7620 (2016)
7. Z.Hu, D.Xie, M.Jin, L.Zhou, J.Li: Relay cooperative beamforming algorithm based on probabilistic constraint in SWIPT secrecy networks. IEEE Access **8**, 173999–174008 (2020)
8. R.Zhang, C.K.Ho: MIMO broadcasting for simultaneous wireless information and power transfer. IEEE Transactions on Wireless Communications **12**(5), 1989–2001 (2013)
9. I.Krikidis, S.Timotheou, S.Nikolaou, G.Zheng, D.W.K.Ng, R.Schober: Simultaneous wireless information and power transfer in modern communication systems. IEEE Communications Magazine **52**(11), 104–110 (2014)
10. J.Xu, L.Liu, R.Zhang: Multiuser MISO beamforming for simultaneous wireless information and power transfer. IEEE Transactions on Signal Processing **62**(18), 4798–4810 (2014)
11. Y.Liu, Z.Ding, M.Elkashlan, H.V.Poor: Cooperative non-orthogonal multiple access with simultaneous wireless information and power transfer. IEEE Journal on Selected Areas in Communications **34**(4), 938–953 (2016)
12. Y.Xu, C.Shen, Z.Ding, X.Sun, S.Yan, G.Zhu, Z.Zhong: Joint beamforming and power-splitting control in downlink cooperative SWIPT NOMA systems. IEEE Transactions on Signal Processing **65**(18), 4874–4886 (2017)
13. F.Zhou, Z.Li, J.Cheng, Q.Li, J.Si: Robust AN-aided beamforming and power splitting design for secure MISO cognitive radio with swipt. IEEE Transactions on Wireless Communications **16**(4), 2450–2464 (2017)
14. H.Wang, X.Xia: Enhancing wireless secrecy via cooperation: Signal design and optimization. IEEE Communications Magazine **53**(12), 47–53 (2015)
15. Y.Liu, H.Chen, L.Wang: Physical layer security for next generation wireless networks: Theories, technologies, and challenges. IEEE Communications Surveys & Tutorials **19**(1), 347–376 (2017)
16. F.Zhou, Z.Chu, Y.Wu, N.Al-Dhahir, P.Xiao: Enhancing PHY security of MISO NOMA SWIPT systems with a practical non-linear EH model. In: 2018 IEEE International Conference on Communications Workshops (ICC Workshops), pp. 1–6 (2018). IEEE
17. Y.Zhang, H.Wang, Q.Yang, Z.Ding: Secrecy sum rate maximization in non-orthogonal multiple access. IEEE Communications Letters **20**(5), 930–933 (2016)
18. Q.Shi, C.Peng, W.Xu, M.Hong, Y.Cai: Energy efficiency optimization for MISO SWIPT systems with zero-forcing beamforming. IEEE Transactions on Signal Processing **64**(4), 842–854 (2016)
19. Z.Chu, Z.Zhu, M.Johnston, SY.LeGoff: Simultaneous wireless information power transfer for MISO secrecy channel. IEEE Transactions on Vehicular Technology **65**(9), 6913–6925 (2016)
20. S.Boyd, L.Vandenberghe: Convex Optimization, (2004)
21. Z.Luo, W.Ma, So, M., Y.Ye, S.Zhang: Semidefinite relaxation of quadratic optimization problems. IEEE Signal Processing Magazine **27**(3), 20–34 (2010)

Figures

Figure 1 The system Model.

Figure 2 The power splitting architecture at user 2.

Figure 3 The minimum transmission power of the BS versus the number of iterations

Figure 4 The minimum transmission power of the BS versus the secrecy rates under different algorithms

Figure 5 The minimum transmission power of the BS versus the secrecy rate of user1

Figure 6 The minimum transmission power of the BS versus the secrecy rate of user 2

Figures

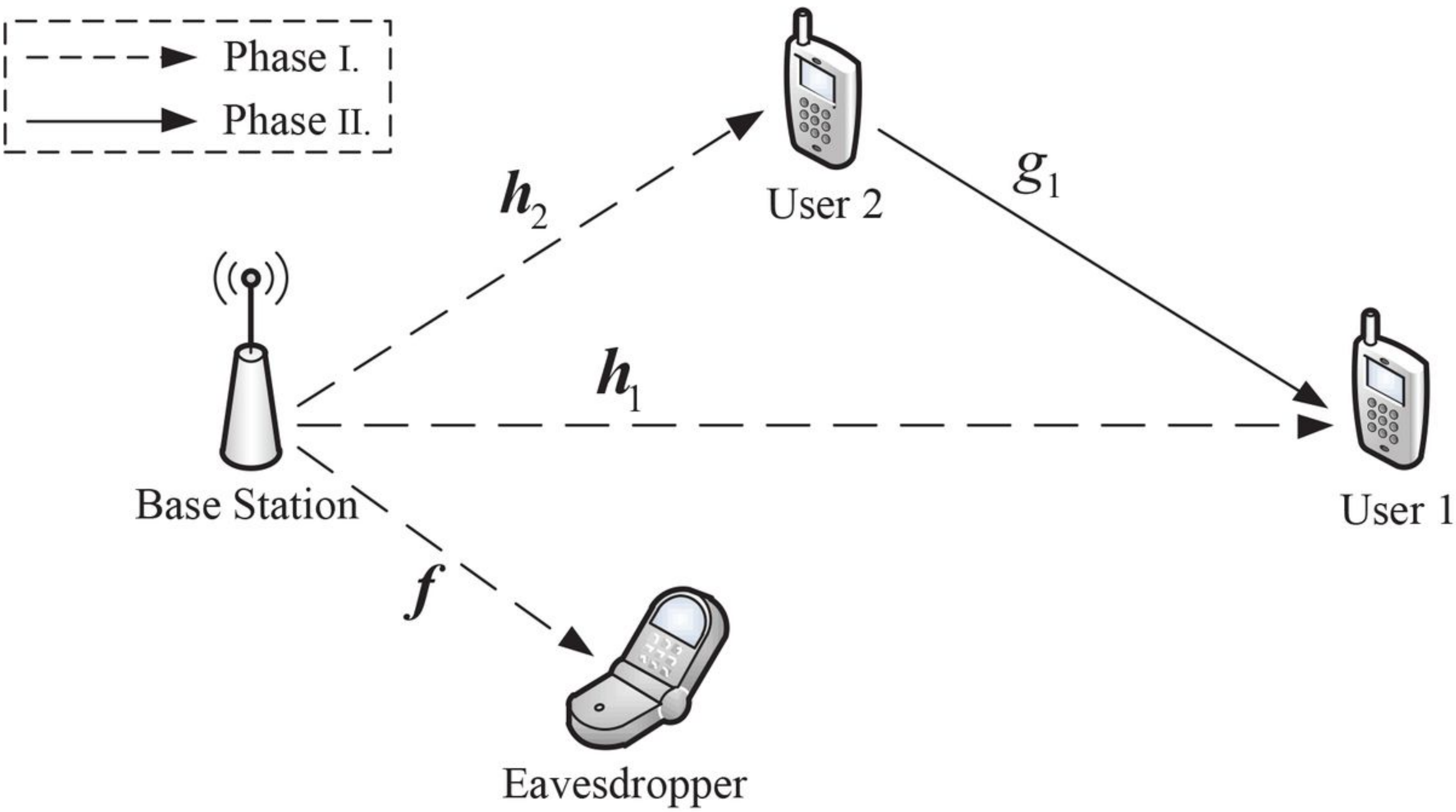

Figure 1

The system Model.

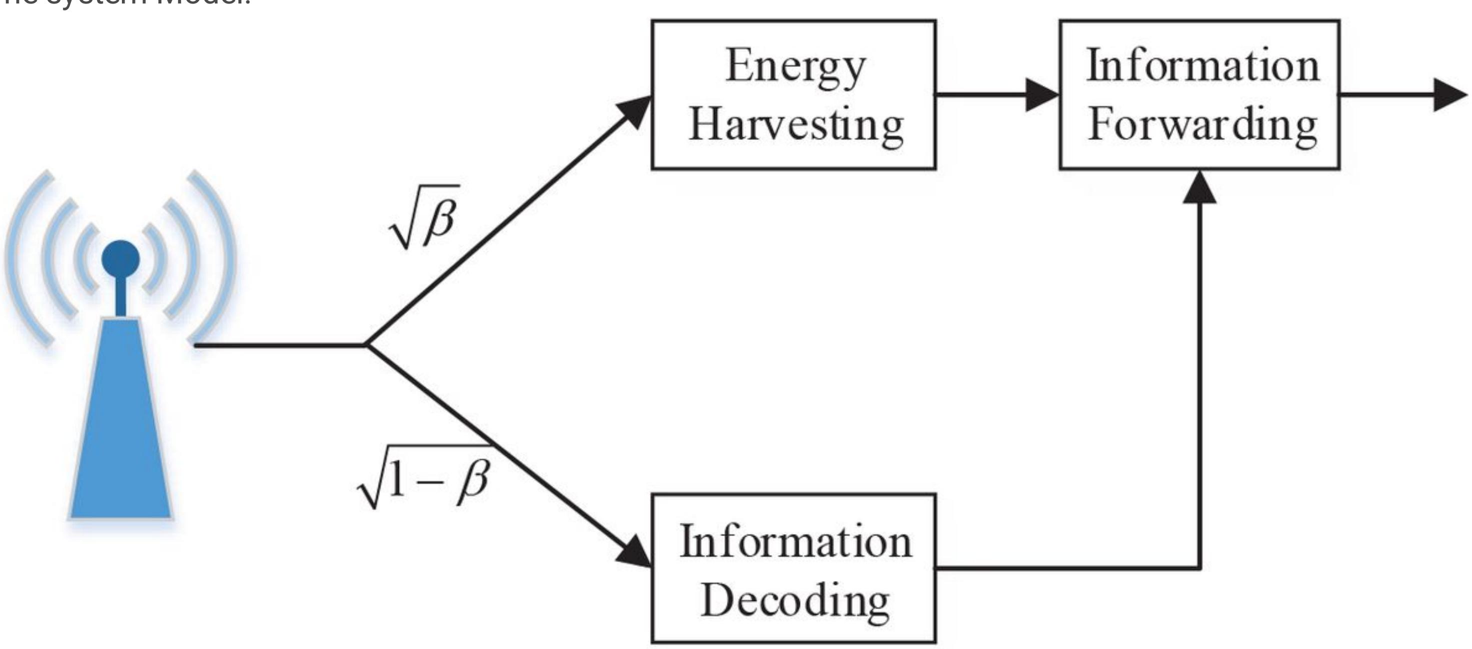

Figure 2

The power splitting architecture at user 2.

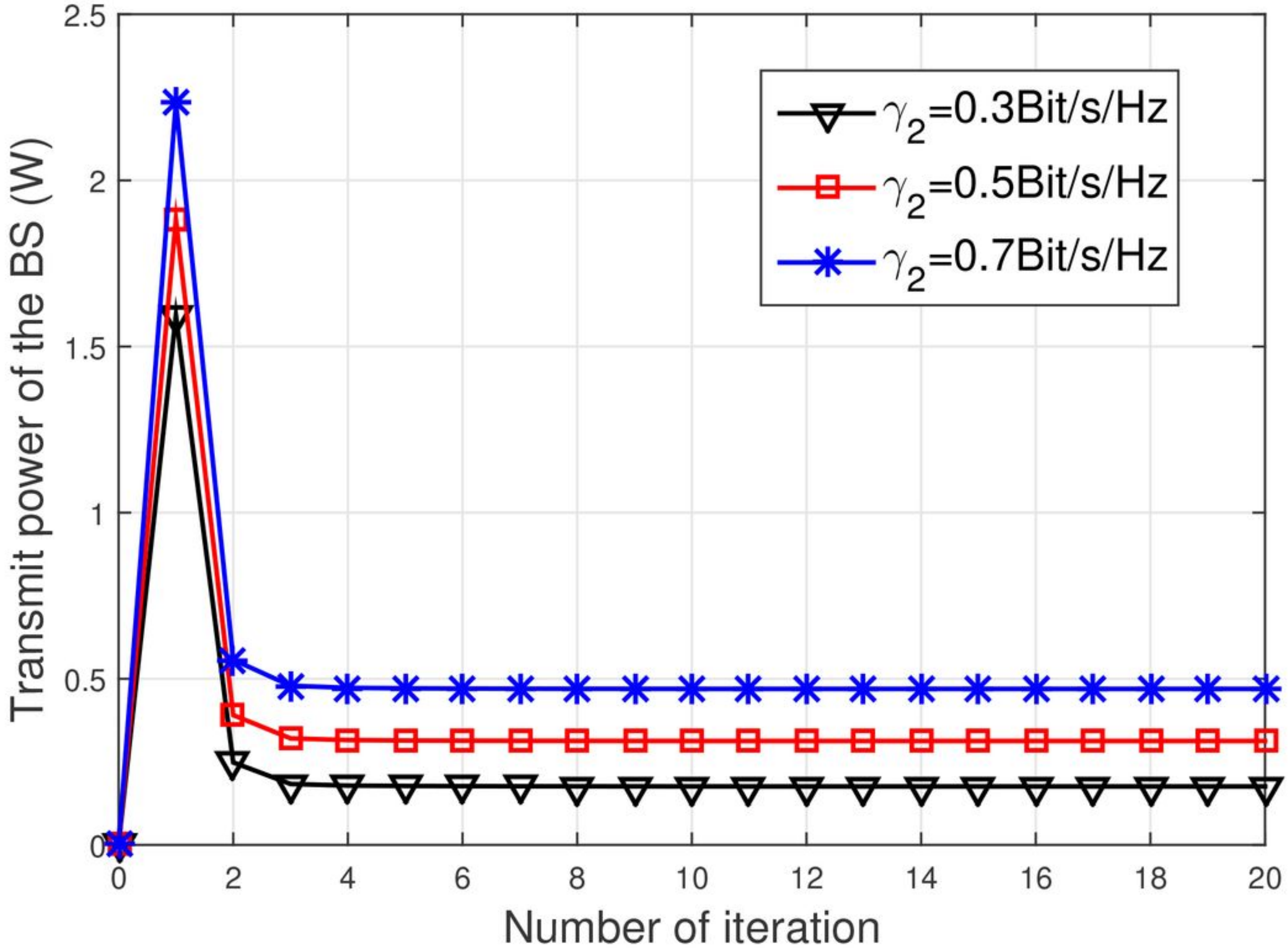

Figure 3

The minimum transmission power of the BS versus the number of iterations

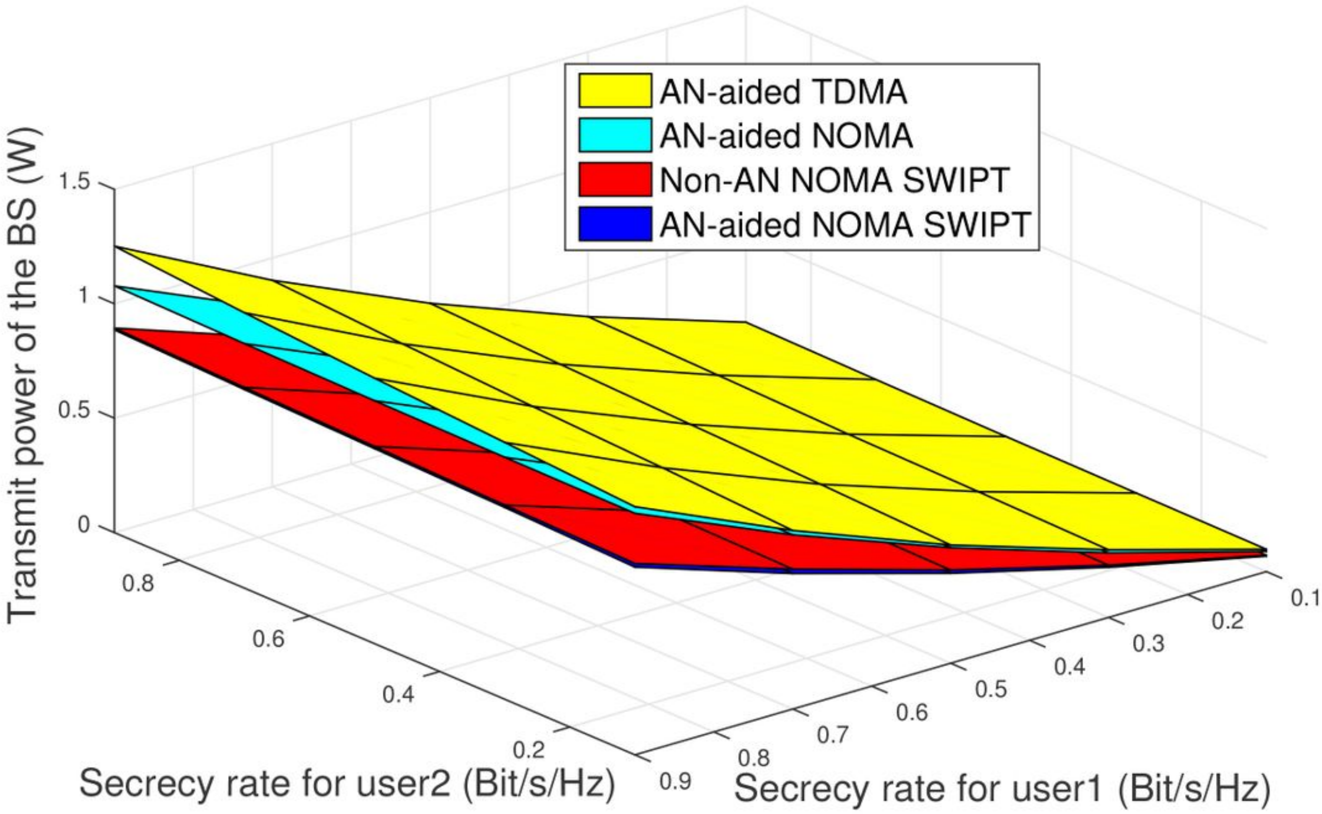

Figure 4

The minimum transmission power of the BS versus the secrecy rates under different algorithms

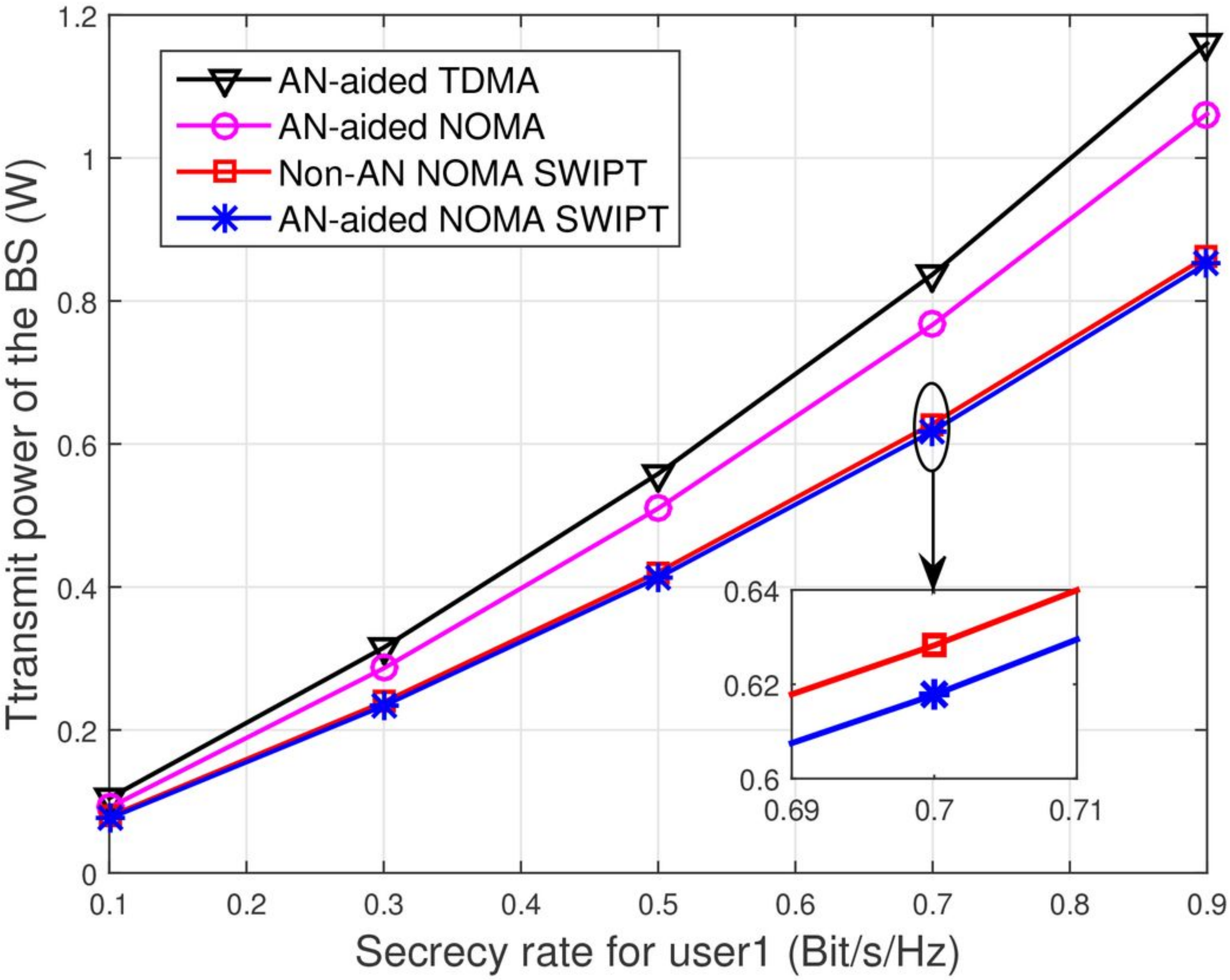

Figure 5

The minimum transmission power of the BS versus the secrecy rate of user1

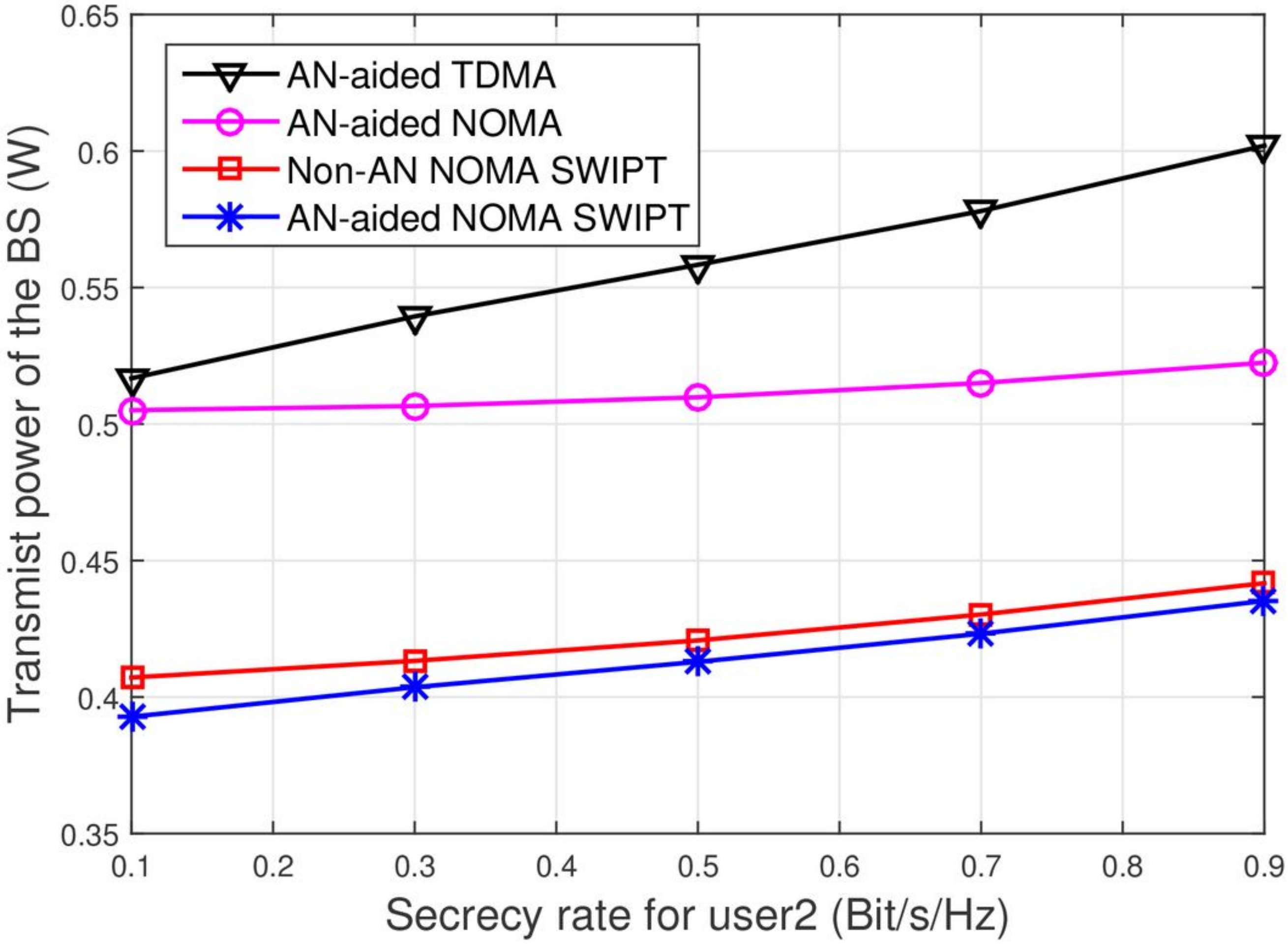

Figure 6

The minimum transmission power of the BS versus the secrecy rate of user 2