IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received May 24, 2019, accepted May 31, 2019, date of publication June 4, 2019, date of current version June 19, 2019.

*Digital Object Identifier 10.1109/ACCESS.2019.2920710*

# Security Energy Efficiency Maximization for Two-Way Relay Assisted Cognitive Radio NOMA Network With Self-Interference Harvesting

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This work was supported in part by the Natural Science Foundation under Project 61501185, in part by the Natural Science Foundation of Hebei Province under Project F2016502062, and in part by the Fundamental Research Funds for the Central Universities under Project 2015MS95.

**ABSTRACT** The security energy efficiency (SEE) is investigated in a two way-full duplex (TW-FD) relay assisted cognitive radio non-orthogonal multiple access (CR-NOMA) networks. In order to improve system energy efficiency, the self-interference (SI) of FD can be regarded as a potential source for relay to harvest energy. Our objective is to maximize security energy efficiency of the secondary user (SU) system subject to harvested energy and the quality of service (QoS) of the users. Specifically, the multi-objective optimization problem is decomposed into three subproblems, i.e., the optimization of transmitting covariance matrix, power allocation, and power splitting ratio. The problem with optimizing transmit covariance matrix is non-convex, hence the semi-determined relaxation algorithm based on the first-order Taylor series expansion function is proposed to solve it. Besides, the multi-objective iterative algorithm (MOIA) is further proposed to achieve the joint optimal solution. The simulation results show that under the same constrains of power allocation and energy harvested, the proposed scheme of two way-full duplex self-interference harvest has significant performance gain on security energy efficiency over the self-interference cancellation.

**INDEX TERMS** Cognitive radio, NOMA, security energy efficiency, self-interference, two-way relay.

## I. INTRODUCTION

Non-orthogonal multiple access (NOMA) has been considered as a promising technology to improve spectrum efficiency, provide massive connectivity and reduce latency [1], [2]. Difference from the traditional orthogonal multiple access (OMA), NOMA services multi-users with the same resource, in which users are distinguished by different power levels. The successive interference cancellation (SIC) is installed at the receiver to mitigate the mutual interference imposed by other users [3], [4]. Cognitive radio (CR), as another technology to improve spectrum utilization, has also received extensive attention. Integrating the NOMA technology into CR networks will have great potential to improve spectrum efficiency and increase the number of users of services [5], [6]. Recently, some authors have shown that the CR-NOMA system can significantly improve spectral efficiency compared to CR or NOMA technology [7], [8].

The associate editor coordinating the review of this manuscript and approving it for publication was Hayder Al-Hraishawi.

However, the interference constraint in CR-NOMA can severely limit the achievable rate of the secondary users (SUs). Note that full-duplex (FD) technique adopted in CR-NOMA network has the potential to achieve higher spectrum efficiency, which allow wireless devices to transmit and receive simultaneously on the same channel [9]. In order to improve the throughput of the NOMA network. Reference [10] proposed a cooperative NOMA scheme, where low-priority users act as full-duplex relays to assist the high-priority users. Moreover, the relay selection method was considered, in which weak users with better performance were selected to help the strong users. In [11], the FD relay was applied to assist far NOMA users transmission, which indicated that the FD NOMA was superior to the half duplex (HF) NOMA in terms of outage probability and ergodic sum rate in low signal to noise ratio (SNR) region. Reference [12] analyzed rate region in the FD aided cooperative NOMA system, the developed algorithms were proposed to maximize achievable rate.

Note that all the aforementioned works focus on the one-way-relay (OWR) cooperative transmission, which significantly improves the quality of service (QoS) of users. However, the spectrum utilization is low at a certain level. For this problem, many papers have proved that two-way-relay (TWR) is promising in improving spectrum utilization and QoS of users. Reference [13] studied the spectrum sharing in cognitive networks, the SU with two-way full-duplex (TW-FD) was used to assist the communication between two primary users. When the self-interference was small enough, the proposed TW-FD spectrum sharing protocol can significantly improve the outage performance. Based on [13], [14] investigated the performance of TW-FD for CR networks, where the classic Hungarian method was proposed to maximize data rate. The authors of [15] and [16] conceived the TWR relay selection schemes to assist SUs to transmit, which demonstrated that the relay selection schemes were indeed capable of improving the outage probability. In [17], the closed-form outage probability expressions for fixed-gain and variable-gain of two-way amplify-and-forward relay networks was given. The authors of [18] studied the relay beamforming of imperfect channel state information in cognitive two-way network. References [19] and [20] extended the application of TWR to NOMA system. In [19], a NOMA two-way relay network model based on physical layer security performance optimization was proposed. According to the transmission signal model, a closed expression of traversal security rate was given. The decoding capability of each user was enhanced by rate allocation and continuous group decoding. Reference [20] studied two-way relay non-orthogonal multiple access (TWR-NOMA) system, where two groups of NOMA users exchanged messages with the aid of two-way relay.

Compared to the conventional one way-half duplex (OW-HD) relay, TW-FD has an obvious advantage in improving system transmission rate [14], [19], [20] and outage performance [13], [15], [16], [18]. However, the main limitation in FD operation is self-interference (SI) caused by the signal leakage from the transceiver output to the input [21]. Based on the characteristics of radio frequency (RF) signals, the SI can be regarded as a viable new potential source for energy harvesting (EH), which can expand energy sources [22]. [23] studied the energy harvesting for full-duplex simultaneous wireless information and power transfer (SWIPT) with power splitting. The energy was mainly derived from the received signal and SI, which demonstrated that the energy efficiency can be significantly improved by self-interference cancellation harvesting (SIH). In order to improve the performance of the two-way relay networks, the authors of [24] studied the self-energy recycling. Specifically, FD harvested energy not only from the energy signal, but also from the self-interference of the loopback channel. [25] studied the efficient transmission solutions for wiretap channels with SWIPT, addressed the energy harvesting maximization problem under the constraints of secrecy rate and transmit power.

In addition, due to the broadcast nature of NOMA as well as CR and the dual function of RF signals [26], [27], NOMA CRNs relying on FD-TWR is vulnerable to be eavesdropped. In [28], the cell-edge user as the potential eavesdropper to receive the signal transmitted to central user. Moreover, the secure beamforming and power allocation were designed to maximize the achievable sum secrecy rate of central users. In [29], the transmit antenna selection strategy was proposed to improve the security of legitimate users. Reference [30] investigated the secure of NOMA systems. Considered the practical passive eavesdropping scenario, where the instantaneous channel state of the eavesdropper was unknown. Moreover, the secrecy outage probability was analyzed. Reference [31] studied the secrecy sum rate optimization for downlink multiple-input multiple-output (MIMO) NOMA, the objective was to maximize achievable secrecy sum rate subject to the constraints of successful successive interference cancellation and transmit power. Reference [32] studied the reliability and security performance of cooperative CR-NOMA, in order to limit the interference of the cognitive base station to the primary user, a mobile association scheme was introduced. In [33], a downlink cascaded transmitting zero-forcing-beamforming (ZFBF) technique was proposed to achieve secure communications in a two-cell multiple-input multiple-output CR-NOMA. In [34], a downlink security-aware resource allocation problem with delay constraint was investigated. In order to improve the physical layer security of CR-NOMA system, [35] proposed an artificial-noise-aided cooperative jamming scheme.

### A. MOTIVATION AND CONTRIBUTIONS

While the previous research has considered the FD to assist SU transmit in CR-NOMA, but the relay is only the OWR, the rate and the spectrum utilization are low. TWR as a cooperative relay, which can significantly improve spectrum efficiency. Obviously, the application of TWR to CR-NOMA is a promising approach to improve the spectral efficiency and sum rate. To the best of our knowledge, there is no contribution to investigate the performance of OWR in the CR-NOMA. Moreover, it seems that there is no contribution to study the security of CR-NOMA system based on TWR. However, due to the broadcast nature of NOMA as well as CR and the dual function of RF signals, CR-NOMA with cooperative relay is vulnerable to be eavesdropped. Consider the relay nodes may have limited battery reserves and characteristics of radio frequency (RF) signals, the SI of FD can be regarded as a viable new potential source for relay to harvest energy. Motivated by these, we investigate the performance of TWR CR-NOMA network with self-interference harvesting.

Due to the large capacity and excessively high complexity, the previous joint optimization algorithm is not suited to cognitive NOMA network with TWR, whose security energy efficiency problem is generally more complicated than the traditional CR systems. Note that the security energy efficiency (SEE) maximization problem has been investigated in [5] and [36]. Specifically, in order to maximize the secure energy efficiency, [5] proposed an iterative algorithm to optimize the transmission power and intensity. However, it is the suboptimal optimization without considering the interference constraint and the power allocation. In addition, although the secure energy efficiency maximization problem has also been studied in [36], it greatly differs from problem considered in this paper. While [36] studied the physical-layer security in CR system without relay assisted transmission. The proposed algorithm was only carried out in two-stage, which not considered the joint optimization. In this paper, in order to obtain optimal solution of security energy efficiency, an alternate iteration algorithm is proposed to jointly optimize transmit covariance matrix, power allocation and power splitting coefficient. Moreover, the problem with optimizing transmit covariance matrix is non-convex, hence the semi-determined relaxation algorithm based on the first-order Taylor series expansion function is proposed to solve it.

The main contributions are summarized as follows:

- The self-interference harvesting scheme is proposed for CR-NOMA with TW-FD in order to improve the security energy efficiency of the secondary network. By using this scheme, the TW-FD is applied to exchange information of two pair of NOMA users. Taking the SI harvesting and the PLS into account, the power splitting (PS) ratios and transmission covariances are jointly designed to maximize the SEE, which make a tradeoff between the security rate and energy efficiency.
- Under the constrains of the QoS of users and the minimum energy harvested, a closed expression of the SEE is formulated with the physical layer security rate and actual energy consumption. Fractional programming is introduced to convert the original fraction optimization into tractable integral expression.
- The objective function is a non-convex and complex multi-objective optimization problem. To tackle the problem, transformed it into three single-objective problem. The semi-determined relaxation algorithm based on the first-order Taylor series expansion function is proposed to convert the problem into convex function. In order to get the optimal solution of SEE, an alternative iterative algorithm is proposed to solve it.
- Simulation results show that compared with the traditional SIC system, the proposed scheme not only improves the spectrum utilization, but also increase the security energy efficiency of the SUs. Finally, we demonstrate that the proposed algorithms can rapidly convergence within few iterations

### B. ORGANIZATION

The remainder of this paper is organized as follows. The system model is presented in Section II. We formulate the optimization problem in detail and describe its solutions in Section III and Section IV, respectively. Simulation results are presented in Section V. Finally, we draw our conclusions in Section VI.

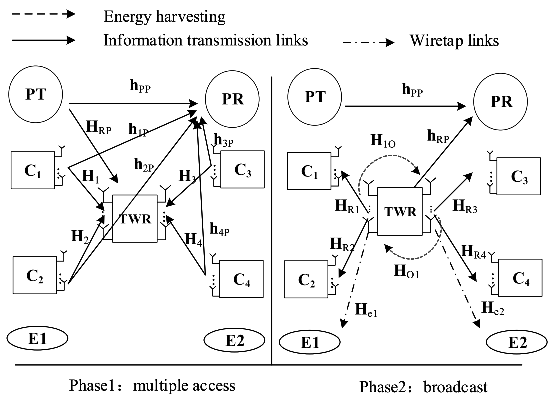


**FIGURE 1. The system model of two-way relay CR-NOMA.**

## II. SYSTEM MODEL

The CR-NOMA system model based on two-way full-duplex relay as shown in Figure 1, which consists of a pair of PU, a two-way relay and two pairs of SUs $C_1$ $C_2$ and $C_3$ $C_4$. As show in Fig.1, $C_1$ and $C_3$ are the nearby users, $C_2$ and $C_4$ are the distant users. We assume the primary transmitter (PT) and primary receiver (PR) have a single antenna, the TWR and SUs are equipped with $M$ and $N$ antennas, respectively, all links are modeled by Rayleigh fading. It assumes that there is no direct link between two pair of SUs due to the fact of high path loss. The exchange of information between two pair of SUs is facilitated via the TWR. Specifically, in the cognitive network, SUs transmits the signals to TWR with the uplink NOMA. After the information is decoded by TWR, which is sent to the paired secondary user. To facilitate analysis, the idealize DF protocol is considered, where TWR is capable of decoding the users' information correctly. To elaborate, the transmission is divided into two time slots, the multiple access time slot and broadcast time slot. It is worth noting that in order to better distinguish the symbols in the paper, we have tabulated the notations used throughout the manuscript. Please refer to Appendix A.

Multiple-Access Slot: SUs transmits the signals to TWR just as the uplink NOMA. In order to reduce the energy limitation of the TWR, simultaneous wireless information and power transmission (SWIPT) is adopted. It is assumed that the power splitting receivers are used to receive the information and harvest energy at the TWR, $\sqrt{\rho_0}$ is used for information detection, while $\sqrt{1-\rho_0}$ for energy harvesting. The relay received information and harvested energy at the TWR are respectively given by

$$y_R = \sqrt{\rho_0}(\sum_{i=1}^{4} \mathbf{H}_i \sqrt{a_i p_s} x_i + \mathbf{H}_{PR}\sqrt{p_t} s_n) + \mathbf{n}_R \tag{1}$$

$$E_{R1} = \eta(1-\rho_0)(\sum_{i=1}^{4} a_i p_s \left\|\mathbf{H}_i\right\|^2 + \left\|\mathbf{H}_{PR}\right\|^2 p_t) \tag{2}$$

where $\mathbf{H}_i \in \mathbb{C}^{M\times N}$ denotes the channel between the $C_i$ and TWR. Without loss of generality, it is assumed that $\|\mathbf{H}_2\|^2 < \|\mathbf{H}_1\|^2$, $\|\mathbf{H}_4\|^2 < \|\mathbf{H}_3\|^2$. $\mathbf{H}_{PR} \in \mathbb{C}^{M\times 1}$ is the channel between PT and TWR, $x_i$ is the signal for TWR. $p_s$ and $p_t$ are the transmit power of SUs and PU, respectively. $a_i(i = 1, 2, 3, 4)$ denotes the power allocation factor of SUs with $a_1 < a_2, a_3 < a_4$. $\eta$ is the energy conversion efficiency, $\mathbf{n}_R \sim CN(0, \delta^2\mathbf{I})$ is the Gaussian noise at TWR. For the received signal, the TWR first decodes $x_2$, the rate of which is given by

$$R_{S2} = \frac{1}{2}\log(1 + \frac{\rho_0 a_2 p_s \|\mathbf{H}_2\|^2}{\tau_1 + \rho_0 p_t \left\|\mathbf{H}_{PR}^2\right\| + \delta_{R2}^2}) \tag{3}$$

where $\tau_1 = \sum_{i=1, i\neq 2}^{4} \rho_0 a_i p_s \|\mathbf{H}_i\|^2$, $\delta_{R2}^2$ is the noise power at the TWR. TWR clears $x_2$ signal by serial interference cancellation (SIC), and then decodes the $x_1$ signal. The rate at TWR to decode $x_2$ is given by

$$R_{S1} = \frac{1}{2}\log(1 + \frac{\rho_0 a_1 p_s \|\mathbf{H}_1\|^2}{\tau_2 + \rho_0 p_t \left\|\mathbf{H}_{PR}^2\right\| + \delta_{R2}^1}) \tag{4}$$

where $\tau_2 = \sum_{i=3}^{4} \rho_0 a_i p_s \|\mathbf{H}_i\|^2$.

Similarly, the signals $x_3$ and $x_4$ can be decoded in the same way. Considering the decoding efficiency of TWR, $R_m$ denotes the minimum decoding rate of TWR, which should satisfy as follows.

$$min(R_{S1}, R_{S2}) \geq R_m \tag{5}$$

Broadcast Slot: the information is exchanged between the $C_1$ $C_2$ and $C_3$ $C_4$ by the virtue of TWR. Therefore, just like the downlink NOMA, TWR transmits the superposed signals $\sqrt{\gamma_1}\mathbf{x}_1 + \sqrt{\gamma_2}\mathbf{x}_2$ and $\sqrt{\gamma_3}\mathbf{x}_3 + \sqrt{\gamma_4}\mathbf{x}_4$ to $C_1$ $C_2$ and $C_3$ $C_4$, respectively. Where $\gamma_i(i = 1, 2, 3, 4)$ denotes the power allocation of TWR with $\gamma_1 + \gamma_2 = 1$, $\gamma_3 + \gamma_4 = 1$. $\mathbf{x}_i(i = 1, 2, 3, 4)$ is the transmit signal of the TWR, which is expressed as

$$\mathbf{x}_i = \mathbf{s}_i \mathbf{w}_i \tag{6}$$

where $\mathbf{s}_i = [\mathbf{s}_{i1}, \mathbf{s}_{i2}, \ldots\ldots \mathbf{s}_{iM}]^T (i = 1, 2, 3, 4)$ is the data stream of signal $\mathbf{x}_i$, $\mathbf{w}_i = [\mathbf{w}_{i1}, \mathbf{w}_{i2}, \ldots\ldots \mathbf{w}_{im}]$ is the transmit beamforming vector corresponding to the transmit data stream. The signals received at the $C_1$ and $C_2$ can be written as.

$$y_1 = \mathbf{H}_{R1}(\sqrt{\gamma_1}\mathbf{x}_1 + \sqrt{\gamma_2}\mathbf{x}_2) + \mathbf{n}_1 \tag{7}$$
$$y_2 = \mathbf{H}_{R2}(\sqrt{\gamma_1}\mathbf{x}_1 + \sqrt{\gamma_2}\mathbf{x}_2) + \mathbf{n}_2 \tag{8}$$

where $\mathbf{H}_{Ri} \in \mathbb{C}^{N\times M}(i = 1, 2, 3, 4)$ is the channel between TWR and SUs with $\|\mathbf{H}_{R2}\mathbf{w}_2\|^2 < \|\mathbf{H}_{R1}\mathbf{w}_1\|^2$, $\mathbf{n}_i$ is the noise at SUs, $\mathbf{n}_i \sim CN(0, \mathbf{I}\delta^2)$.

According to NOMA protocal, the rate of $C_1$ and $C_2$ are respectively given as

$$R_1 = \frac{1}{2}\log\left|\mathbf{I} + \xi\mathbf{H}_{R1}\mathbf{Q}_1\mathbf{H}_{R1}^H\gamma_1\right| \tag{9}$$
$$R_2 = \frac{1}{2}\log\left|\mathbf{I} + \frac{\xi\mathbf{H}_{R2}\mathbf{Q}_2\mathbf{H}_{R2}^H\gamma_2}{\mathbf{I} + \xi\mathbf{H}_{R2}\mathbf{Q}_1\mathbf{H}_{R2}^H\gamma_1}\right| \tag{10}$$

where $\xi = \frac{1}{\|\mathbf{n}_1\|^2} = \frac{1}{\|\mathbf{n}_2\|^2}$, $\mathbf{Q}_1 \in \mathbb{C}^{M\times M}$ and $\mathbf{Q}_2 \in \mathbb{C}^{M\times M}$ are the covariances of signals $\mathbf{x}_1$ and $\mathbf{x}_2$.

In order to guarantee the ability of $C_1$ to decode the massage of $C_2$, it is necessary to satisfy

$$R_{1\to 2} = \frac{1}{2}\log\left|\mathbf{I} + \frac{\xi\mathbf{H}_{R1}\mathbf{Q}_2\mathbf{H}_{R1}^H\gamma_2}{\mathbf{I} + \xi\mathbf{H}_{R1}\mathbf{Q}_1\mathbf{H}_{R1}^H\gamma_1}\right| \geq R_{th} \tag{11}$$

where $R_{1\to 2}$ denotes the rate of $C_1$ to decode the message of $C_2$, $R_{th}$ is a target rate to achieve efficient SIC at $C_1$.

Since TWR adopts FD, the main challenge of the FD is self-interference. Usually, self-interference cancellation is used to reduce its impact. In this paper, from the aspect of system energy efficiency, the SI of FD is used for energy harvest, which reduce the actual energy consumption of the TWR. Since the two-side users have the same transmission mechanism, for convenience, we only consider the self-interference generated by the signal $\sqrt{\gamma_1}\mathbf{x}_1 + \sqrt{\gamma_2}\mathbf{x}_2$. So that the SI received by the TWR is given by $y_{S1} = \mathbf{H}_{O1}(\sqrt{\gamma_1}\mathbf{x}_1 + \sqrt{\gamma_2}\mathbf{x}_2)$. In order to reduce the SI of TWR, the perfect self-interference cancellation technique is considered. And then the energy harvesting by the TWR from SI can be formulated as

$$E_R = \eta(1 - \rho_0)(\sum_{i=1}^{2}\gamma_i tr(\mathbf{H}_{O1}Q_i\mathbf{H}_{O1}^H)) \tag{12}$$

where $\mathbf{H}_{O1} \in \mathbb{C}^{M\times M}$ is the loopback channel gain from transmitter to receiver of TWR.

Meanwhile, due to the broadcast nature of wireless channels, the signal transmitted by TWR will be overheard by $E_1$ and $E_2$. For the convenience, only one-sided users are considered. Thus, the signal received of the $E_1$ can be given by

$$y_e = \mathbf{H}_{e1}(\sqrt{\gamma_1}\mathbf{x}_1 + \sqrt{\gamma_2}\mathbf{x}_2) + \mathbf{n}_e \tag{13}$$

where $\mathbf{H}_{e1}$ denotes the channel gain from TWR to $E_1$. In order to ensure the secure transmission of secondary users. We assumed that the channel condition satisfies $\|\mathbf{H}_{e1}\mathbf{w}_{e1}\|^2 < \|\mathbf{H}_{R2}\mathbf{w}_2\|^2 < \|\mathbf{H}_{R1}\mathbf{w}_1\|^2$. According to the NOMA protocol, the rate of $E_1$ to overhear $C_1$ and $C_2$ are respectively given by

$$R_e^1 = \frac{1}{2}\log\left|\mathbf{I} + \xi\mathbf{H}_{e1}\mathbf{Q}_1\mathbf{H}_{e1}^H\gamma_1\right| \tag{14}$$
$$R_e^2 = \frac{1}{2}\log\left|\mathbf{I} + \frac{\xi\mathbf{H}_{e1}\mathbf{Q}_2\mathbf{H}_{e1}^H\gamma_2}{\mathbf{I} + \xi\mathbf{H}_{e1}\mathbf{Q}_1\mathbf{H}_{e1}^H\gamma_1}\right| \tag{15}$$

Therefore the sum rate of the eavesdroppers is expressed as $R_e = R_e^1 + R_e^2$.

In underlay CRN, SUs can share PUs spectrum as long as the interference inflicted on the PU can not affect the quality of service of the primary user. Without loss of generality, in the second time the transmission rate at the PU is given by

$$R_P = \frac{1}{2}\log_2\left(1 + \frac{p_t\left\|\mathbf{h}_{pp}\right\|^2}{2\mathbf{h}_{RP}(\mathbf{Q}_1 + \mathbf{Q}_2)\mathbf{h}_{RP}^H + \delta_P^2}\right) \tag{16}$$

where $\mathbf{h}_{RP}$ and $\mathbf{h}_{PP}$ denote the channel from TWR to PR and PT to PR, respectively. The sum rate of $C_1$ and $C_2$ can be written as

$$R_{tot} = R_1 + R_2 \tag{17}$$

The actual energy consumption of SUs system is obtained by

$$P_{tot} = tr\left(\mathbf{Q}_1 + \mathbf{Q}_2\right) + P_l + P_r \tag{18}$$

where $P_r$ is the transmission power of TWR, $P_l$ is the link power consumption. Based on (2) and (12), the total energy harvested of TWR is given by

$$E_{tot} = E_{R1} + E_R \tag{19}$$

## III. PROBLEM FORMULATION

In this section, we proposed to analyze the security rate of SUs. Then, the security energy efficiency can be further deduced, which is defined as the ratio of security rate to the actual energy consumption. Assume that two pairs of SUs have the same transmission performance, for the convenience, only users $C_1$ and $C_2$ are considered. Thus the security rate of SUs can be formulated as

$$\begin{aligned} R_s = R_{tot} - R_e = &\frac{1}{2}\log_2\left|\mathbf{I} + \xi\mathbf{H}_{R1}\mathbf{Q}_1\mathbf{H}_{R1}^H\gamma_1\right| \\ &+ \frac{1}{2}\log_2\left|\mathbf{I} + \frac{\xi\mathbf{H}_{R2}\mathbf{Q}_2\mathbf{H}_{R2}^H\gamma_2}{\mathbf{I} + \xi\mathbf{H}_{R2}\mathbf{Q}_1\mathbf{H}_{R2}^H\gamma_1}\right| \\ &- \frac{1}{2}\log_2\left|\mathbf{I} + \xi\mathbf{H}_{e1}\mathbf{Q}_1\mathbf{H}_{e1}^H\gamma_1\right| \\ &- \frac{1}{2}\log_2\left|\mathbf{I} + \frac{\xi\mathbf{H}_{e1}\mathbf{Q}_2\mathbf{H}_{e1}^H\gamma_2}{\mathbf{I} + \xi\mathbf{H}_{e1}\mathbf{Q}_1\mathbf{H}_{e1}^H\gamma_1}\right| \end{aligned} \tag{20}$$

Consequently, our goal is to maximize the security energy efficiency of SUs system by optimizing the transmission covariance and power allocation coefficients. To the end, the optimization problem $p_0$ is formulated as

$$\max_{Q_1,\gamma_1,\rho_0} \eta_{EE} = \frac{R_s}{P_{tot} - E_{tot}} \tag{21}$$
$$s.t.\ R_P \geq R_0 \tag{21a}$$
$$min(R_{S1}, R_{S2}) \geq R_m \tag{21b}$$
$$R_{1\to 2} \geq R_{th} \tag{21c}$$
$$E_{tot} \geq E_{th} \tag{21d}$$
$$0 \leq \gamma_1 \leq 1 \tag{21e}$$
$$0 \leq \rho_0 \leq 1 \tag{21f}$$

where $R_0$ and $R_m$ are the thresholds of the minimum transmission rate and decoding rate of PU and TWR, respectively. The constraint (21b) is given to guarantee the efficient SIC in the $S_1$, $R_{th}$ is the rate requirement for successful decoding of the NOMA user. $E_{th}$ denotes minimum energy harvested threshold of the relay.

### A. OPTIMIZATION OF THE COVARIANCE MATRIX $\mathbf{Q}_1$

It is difficult to find the optimal solution of the problem due to the fractional form of the objective function, for which the close-form solution of the security energy efficiency can hardly be derived. In order to reduce the computational complexity, the objective function can be transformed into a maximize problem with parameter $\lambda$ by fractional programming, which can be obtained by $F(\Xi, \lambda) = R_s^* - \lambda(P_{tot} - E_{tot})$, and $\Xi$ is the collection of variable $\mathbf{Q}_1$, $\gamma_1$ and $\rho_0$. We regulate another function as $g(\lambda) = \max(\Xi, \lambda)$, and the root of equation $g(\lambda) = 0$ is the maximum value of the spectral efficiency. For the given $\mathbf{Q}_1$, $\gamma_1$ and $\rho_0$, we exploit the following theorem to find the optimal value $\lambda^*$.

*Theorem 1:* $g(\lambda)$ is convex, continuous and decreasing function of $\lambda$, and the optimal solution of problem $p_0$ exists at $F(\Xi, \lambda) = 0$.

*Proof*: Please refer to Appendix B.

Assume that $\lambda^*$, relay power allocation $\gamma_1$ and secondary user received power splitting $\rho_0$ are given, then the optimal problem can be expressed as $p_1$.

$$\max_{\mathbf{Q}_1} \eta_{EE}(\lambda) = R_s - \lambda(P_{tot} - E_{tot}) \tag{22}$$
$$s.t.\ R_P \geq R_0 \tag{22a}$$
$$R_{1\to 2} \geq R_{th} \tag{22b}$$
$$E_{tot} \geq E_{th} \tag{22c}$$

The problem of $p_1$ is non-convex due to the existing of security rate and the constraints of (22a) and (22b). In the section, the convex approximation based Taylor series expansion is proposed to approximate problem $p_1$.

*Proposition 1*: Based on the Taylor series expansion, $R_s$, $R_P$, and $R_{1\to 2}$ are approximated as

$$\begin{aligned} R_s^* = &\frac{1}{2}\log\left|\mathbf{I} + \mathbf{H}_{R1}\mathbf{Q}_1\mathbf{H}_{R1}^H\gamma_1\right| \\ &+ \frac{1}{2ln2}tr(\mathbf{H}_{R2}^H\Theta_1^{-1}\chi_1\mathbf{H}_{R2}\mathbf{Q}_1) \\ &- \frac{1}{2ln2}tr(\mathbf{H}_{e1}^H\Theta_2^{-1}\chi_2\mathbf{H}_{e1}\mathbf{Q}_1) \\ &- \frac{\xi\gamma_1}{2ln2}tr(\mathbf{H}_{e1}^H(\mathbf{I} + \xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1)^{-1}\mathbf{H}_{e1}\mathbf{Q}_1) + \varphi \end{aligned} \tag{23}$$

$$\begin{aligned} R_P^* = &\frac{1}{2}\log_2(2\mathbf{h}_{RP}(\mathbf{Q}_1 + \mathbf{Q}_2)\mathbf{h}_{RP}^H + \delta^2 + p_t + p_t\mathbf{H}_{pp}) \\ &- \frac{\mathbf{h}_{RP}\mathbf{h}_{RP}^H\mathbf{Q}_1}{ln2(2\mathbf{h}_{RP}(\mathbf{Q}_{10} + \mathbf{Q}_2)\mathbf{h}_{RP}^H + \delta_P^2)} + \varphi_1 \end{aligned} \tag{24}$$

$$R_{1\to 2}^* = \frac{tr\left(\mathbf{H}_{R1}\frac{\xi^2\mathbf{H}_{R1}\mathbf{Q}_2\mathbf{H}_{R1}^H\gamma_2\gamma_1}{(\mathbf{I}+\xi\mathbf{H}_{R1}\mathbf{Q}_{10}\mathbf{H}_{R1}^H\gamma_1)^2}\mathbf{H}_{R1}\mathbf{Q}_1\right)}{2ln2} + \varphi_2 \tag{25}$$

$\Theta_i\ (i = 1, 2)$ and $\chi_i\ (i = 1, 2)$ are respectively given by

$$\begin{cases} \Theta_1 = (\mathbf{I} + \frac{\xi\mathbf{H}_{R2}\mathbf{Q}_2\mathbf{H}_{R2}^H\gamma_2}{\mathbf{I} + \xi\mathbf{H}_{R2}\mathbf{Q}_{10}\mathbf{H}_{R2}^H\gamma_1}) \\ \Theta_2 = (\mathbf{I} + \frac{\xi\mathbf{H}_{e1}\mathbf{Q}_2\mathbf{H}_{e1}^H\gamma_2}{\mathbf{I} + \xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1}) \\ \chi_1 = \frac{\xi^2\gamma_1\gamma_2\mathbf{H}_{R2}\mathbf{Q}_2\mathbf{H}_{R2}^H}{(\mathbf{I} + \xi\mathbf{H}_{R2}\mathbf{Q}_{10}\mathbf{H}_{R2}^H\gamma_1)^2} \\ \chi_2 = \frac{\xi^2\gamma_1\gamma_2\mathbf{H}_{e1}\mathbf{Q}_2\mathbf{H}_{e1}^H}{(\mathbf{I} + \xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1)^2} \end{cases} \tag{26}$$

where $\varphi$, $\varphi_1$ and $\varphi_2$ are the constants for the given $\mathbf{Q}_{10}$.

*Proof*: Please refer to Appendix C.

Based on the above approximation, the problem of $p_1$ can be reformulated as

$$\min_{Q_1} \eta_{EE} = \lambda(P_{tot} - E_{tot}) - R_s^* \tag{27}$$
$$s.t.\ R_P^* \geq R_0 \tag{27a}$$
$$R_{1\to 2}^* \geq R_{th} \tag{27b}$$
$$E_{tot} \geq E_{th} \tag{27c}$$
$$rank(\mathbf{Q}_2) = 1\ qquad \tag{27d}$$

Optimization problem $p_1$ is still non-convex problem due to the existence of the non-convex rank 1 constraint and the coupling between the optimization variables. Therefore, the semi-definite relaxation (SDR) algorithm is proposed to solve it, the optimization problem can be formulated as $p_{10}$

$$\min_{Q_1} \eta_{EE} = \lambda(P_{tot} - E_{tot}) - R_s^* \tag{28}$$
$$s.t.\ \Xi_1 \mathbf{Q}_1 - \frac{1}{2}\log(2\mathbf{h}_{RP}\mathbf{Q}_1\mathbf{h}_{RP}^H + \Gamma_1) \leqslant \varphi_1 - R_0 \tag{28a}$$
$$\frac{tr\left(\mathbf{H}_{R1}^H \frac{\xi^2 \mathbf{H}_{R1}\mathbf{Q}_2\mathbf{H}_{R1}^H \gamma_2\gamma_1}{(\mathbf{I}+\xi\mathbf{H}_{R1}\mathbf{Q}_{10}\mathbf{H}_{R1}^H\gamma_1)^2}\mathbf{H}_{R1}\mathbf{Q}_1\right)}{2ln2} \geq R_{th} - \varphi_2 \tag{28b}$$
$$\eta(1-\rho_0)\left(\gamma_1 tr\left(\mathbf{H}_{O1}\mathbf{Q}_1\mathbf{H}_{O1}^H\right) + \Gamma_2\right) \geq E_{th} - \varphi_2 \tag{28c}$$
$$\begin{cases} \Xi_1 = \mathbf{h}_{RP}\mathbf{h}_{RP}^H/ln2\left(2h_{RP}(\mathbf{Q}_{10}+\mathbf{Q}_2)\mathbf{h}_{RP}^H + \delta_P^2\right) \\ \Xi_2 = \eta(1-\rho_0)\left(\sum_{i=1}^{4} a_i p_s \|\mathbf{H}_i\|^2 + \|\mathbf{H}_{RP}\|^2 p_t\right) \\ \Gamma_1 = 2\mathbf{h}_{RP}\mathbf{Q}_2\mathbf{h}_{RP}^H + p_t\mathbf{H}_{PP} + \delta_P^2 \\ \Gamma_2 = \gamma_2 tr(\mathbf{H}_{O1}\mathbf{Q}_2\mathbf{H}_{O1}^H) \end{cases}$$

The optimization problem is transformed into a convex problem by Taylor formula approximation and SDR. Therefore the convex optimization toolkit can be taken to solve it.

The closed-form expression of the optimal $\mathbf{Q}_1^*$ is obtained through the following theorem 3.2

*Theorem 2:* For the given $\gamma_1$ and $\rho_0$, the optimal solution to $p_{10}$ is obtained by

$$\mathbf{Q}_1^* = \Psi_1^{-\frac{1}{2}}\mathbf{V}_1\Delta\mathbf{V}_1^H\Psi_1^{-\frac{1}{2}} \tag{29}$$

where $\Delta = diag(p_1, \ldots, p_t)$, $p_m = \left(\frac{v}{ln2} - \frac{\sigma^2}{\vartheta_m}\right)$, $m = 1, 2, \ldots, 4$, $v$ denotes the water level, $t = min\{N, M\}$.

$$\mathbf{H}_{R1}\Psi_1^{-\frac{1}{2}} = \mathbf{U}_1\Lambda\mathbf{V}_1^H \tag{30}$$

where $\mathbf{V}_1 \in \mathbb{C}^{N\times t}$ is the right singular vector, $\Lambda = diag(\vartheta_1, \ldots, \vartheta_t)$, $t = min\{N, M\}$, $\vartheta_1, \ldots, \vartheta_t$ are the eigenvalues of $\mathbf{H}_{R1}^H\mathbf{H}_{R1}$.

*Proof:* Please refer to Appendix D.

### B. OPTIMIZATION OF RECEIVED POWER SPLITTING

In this section, we consider the subproblem $p_2$, which optimizes the power splitting of TWR when transmission covariance and power allocation are fixed. As $\rho_0$ is mainly limited by the decoding rate and energy harvesting, the optimization function $p_2$ can be written as

$$\max_{\rho_0} \eta_{EE} = \frac{R_s}{P_{tot} - E_{tot}} \tag{31}$$
$$s.t.\ min(R_{S1}, R_{S2}) \geq R_m \tag{31a}$$
$$E_{tot} \geq E_{th} \tag{31a}$$
$$0 \leq \rho_0 \leq 1 \tag{31a}$$

The security energy efficiency is derived with $\rho_0$, which can be obtained by

$$\frac{d\eta(EE)}{d\rho_0} = \frac{-R_s(X_1+X_2)}{(P_{tot}-E_{tot})^2} \tag{32}$$

where $X_1 = \eta\left(\sum_{i=1}^4 a_i p_s \|\mathbf{H}_i\|^2 + \|\mathbf{H}_{PR}\|^2 p_t\right)$, $X_2 = \eta\left(\sum_{i=1}^2 \gamma_i \mathrm{tr}(\mathbf{H}_{O1}\mathbf{Q}_i\mathbf{H}_{O1}^H)\right)$, $t_1 = \xi\|\mathbf{H}_{O1}\mathbf{x}_1\|^2$, $t_2 = \xi\|\mathbf{H}_{O1}\mathbf{x}_2\|^2$. Because the power allocation satisfies $\gamma_i \geq 0 (i = 1, 2), X_i(i = 1, 2) > 0$, it can be obtained by

$$\frac{d\eta_{EE}}{d\rho_0} \leq 0 \tag{33}$$

From (33), one can observe that the security energy efficiency is a subtractive function about $\rho_0$. Based on the constraint terms (31a), (31b), (31c), the range of $\rho_0$ is obtained by.

$$max(\rho_{01}, \rho_{02}) \leq \rho_0 \leq \rho_3$$
$$\begin{cases} \rho_{01} = R_M\sigma_{R2}^2/(a_2 p_s \|\mathbf{H}_2\|^2 - R_M\Delta_1) \\ \rho_{02} = R_M\sigma_{R1}^2/(a_2 p_s \|\mathbf{H}_1\|^2 - R_M\Delta_2) \\ \rho_{03} = 1 - E_{th}/\eta\,[\sum_{i=1}^{2}\gamma_i tr(\mathbf{H}_{O1}\mathbf{Q}_i\mathbf{H}_{O1}^H) + \Delta_3] \end{cases} \tag{34}$$

where $\Delta_1 = \sum_{i=1,i\neq 2}^4 a_i p_s \|\mathbf{H}_i\|^2 + p_t\|\mathbf{H}_{PR}\|^2$, $\Delta_2 = \sum_{i=3}^4 a_i p_s \|\mathbf{H}_i\|^2 + p_t\|\mathbf{H}_{PR}\|^2$, $\Delta_3 = (\sum_{i=1}^4 a_i p_s \|\mathbf{H}_i\|^2 + \|\mathbf{H}_{PR}\|^2)$.

Consequently, for the given $\gamma_1^*$ and $Q_1^*$, the closed-form expression of the optimal power splitting can be obtained by

$$\rho_0^* = max(\rho_{01}, \rho_{02}) \tag{35}$$

### C. OPTIMIZATION OF POWER ALLOCATION

In this section, we focus on the case where the relay transmit covariance matrix $\mathbf{Q}_1^*$ and power splitting $\rho_0^*$ are given to optimize power allocation, which is formulated as.

$$\max_{\gamma_1} \eta_{EE} = \frac{R_s}{P_{tot} - E_{tot}} \tag{36}$$
$$\frac{\xi\|\mathbf{H}_{R1}\mathbf{x}_2\|^2\gamma_2}{1+\xi\|\mathbf{H}_{R1}\mathbf{x}_1\|^2\gamma_1} \geq 2^{2R_{th}} - 1 \tag{36a}$$
$$\eta(1-\rho_0)\left(\sum_{i=1}^{2}\gamma_i tr(\mathbf{H}_{O1}\mathbf{Q}_1\mathbf{H}_{O1}^H)\right) \geq E_{th} - E_{R1} \tag{36b}$$
$$0 \leq \gamma_1 \leq 1 \tag{36c}$$

According to constraints (36a), (36b) and (36c), the range of $\gamma_1$ can be formulated as

$$max(0, (D_1 - D_2)/D_3) \leq \gamma_1 \leq min(D_4/D_5, 1) \tag{37}$$

$D_1 = (E_{th} - E_{R1})/\eta(1-\rho_0)$, $D_2 = \gamma_2 tr(\mathbf{H}_{O1}\mathbf{Q}_2\mathbf{H}_{O1}^H)$, $D_3 = tr(\mathbf{H}_{O1}\mathbf{Q}_1\mathbf{H}_{O1}^H)$, $D_4 = \xi \|\mathbf{H}_{R1}\mathbf{x}_2\|^2 - (2^{2R_{th}} - 1)$, $D_5 = (2^{2R_{th}} - 1)\xi \|\mathbf{H}_{R1}\mathbf{x}_1\|^2 + \xi \|\mathbf{H}_{R1}\mathbf{x}_2\|^2$.

Algorithm 1 is proposed to solve the optimal power allocation in TABLE 1.

**TABLE 1. Algorithm 1 bisection search based power allocation.**

1: Initialization $\rho_0$, $E_{th}$, $\eta$, $\xi$, $R_{th}$, convergence factor $\epsilon$.
2: Calculate according to equation (37), set $\gamma_{max} = min(\frac{D_4}{D_5}, 1)$, and $\gamma_{min} = max(0, (D_1 - D_2)/D_3)$, $\gamma = (\gamma_{max} + \gamma_{min})/2$.
3: if $\gamma_{max} - \gamma_{min} \geq \epsilon$, go to step 5.
4: else go to step 10
5: Calculate $R_{1\rightarrow 2}(\gamma)$ and $E_R(\gamma)$ according to equation (11) and (12).
6: if $R_{1\rightarrow 2}(\gamma) \geq R_{th}$ and $E_R(\gamma) \geq E_{th} - E_{R1}$, $\gamma_{max} = \gamma$
7: else $\gamma_{min} = \gamma$
8: if $R_{1\rightarrow 2}(\gamma) \geq R_{th}$ and $E_R(\gamma) \geq E_{th} - E_{R1}$. $\gamma = \gamma_{max}$, return step2
9: else $\gamma = \gamma_{min}$, return step2
10: Output: optimal power allocation $\gamma_1^* = \gamma$ and $\gamma_2^* = 1 - \gamma_1^*$

### D. ALTERNATE ITERATION ALGORITHM FOR JOINT OPTIMIZATION

In order to maximize the security energy efficiency with transmission signal covariance $\mathbf{Q}_1$, TWR power allocation $\rho_0$ and $\gamma_1$. For this part, an multi-objective iterative Algorithm 2 is proposed as shown in TABLE 2.

**TABLE 2. Algorithm 2 multi-objective iterative algorithm (MOIA).**

1: Initialize $\eta = 0.8$ , relay transmit power $p_l$, other link power consumption $p_s$ constraint function threshold $R_0$, $R_m$, $R_{th}$ and $E_{th}$, the number of iterations $i = 0$, tolerance $\epsilon$, $\rho_0^{(0)} = 0.5$ $\gamma_1 = 0.5$, $\eta_{EE}^{(0)} = -\epsilon$, $\eta_{EE}^{(-1)} = \eta_{EE}^{(0)} - \epsilon$
2: iternation:
3: While $\left|\eta_{EE}^{(i)} - \eta_{EE}^{(i-1)}\right| \geq \epsilon$
4: $i = i + 1$
5: Obtain the covariance matrix $\mathbf{Q}_1^{(i)}$, with $\rho_0^{(i-1)}$, $\gamma_1^{(i-1)}$ by (29).
6: Calculate the optimal power allocation $\rho_0^{(i)}$,with $\mathbf{Q}_1^{(i)}$,$\gamma_1^{(i-1)}$ by (35).
7: Obtain the power splitting $\gamma_1^{(i)}$,with $\rho_0^{(i)}$, $\mathbf{Q}_1^{(i)}$ by Algorithm 1
8: Update $\eta_{EE}^{(i)}$ with $\mathbf{Q}_1^{(i)}$, $\rho_0^{(i)}$, $\gamma_1^{(i)}$ by (21)
9: end while
10: Output:$\mathbf{Q}_1^*$, $\rho_0^*$, $\gamma_1^*$, $\eta_{EE}^*$

## IV. NUMERICAL RESULTS

In this section, simulation results are given to evaluate the system performance and investigate the impact levels of FD-TWR on security energy efficiency for CR-NOMA. Simulation parameters used are summarized in TABLE 4. Without loss of generality, we employ the Rayleigh fading channel $\mathbf{g}_i \in \mathbb{C}^{M\times N}(i = 1, 2, 3, 4)$, the channels from TWR to SUs are modeled as $\mathbf{H}_{Ri} = d_i^{-a/2}\mathbf{g}_i(i = 1, 2, 3, 4)$, $a$ is the average path loss [20].

Fig.2 represents the security energy efficiency versus the iteration number for different initializations of $(\rho_0, \mathbf{Q}_1, \gamma_1)$ with Algorithm 2. It can be seen that the proposed algorithm has fast convergence after 7-9 iterations.

Fig.3 illustrates the security energy efficiency versus the receive power allocation of TWR with different energy conversion efficiency, when $E_{min} = 50\mu W$, $R_m = 0.2bit/s$, $\rho_0 = 0.2$, $P_r = 38dBm$. It can be observed that when $0.035 \leq \gamma_1 \leq 0.5$, security energy efficiency increases with the $\gamma_1$. This can be well understood that in order to meet the minimum energy harvested threshold, the power allocation cannot be reduced indefinitely. Additionally, one can observed that under the same power allocation factor and

**TABLE 3. Table of parameters for numerical results.**

| | |
|---|---|
| Monte Carlo simulations repeated | $10^6$ iterations |
| Average pass loss exponent | $\alpha = 2$ |
| The distance between R and $C_1$ or $C_3$ | $d_1 = 2m, d_3 = 2m$ |
| The distance between R and $C_2$ or $C_4$ | $d_2 = 10m, d_4 = 10m$ |
| Link power consumption | $P_l = 10dBm$ |
| Number of antennas of SU | $N = 3$ |
| Threshold of NOMA decoding rate | $R_{th} = 0.2bit/s$ |
| Minimum rate of PU | $R_0 = 0.5bit/s$ |

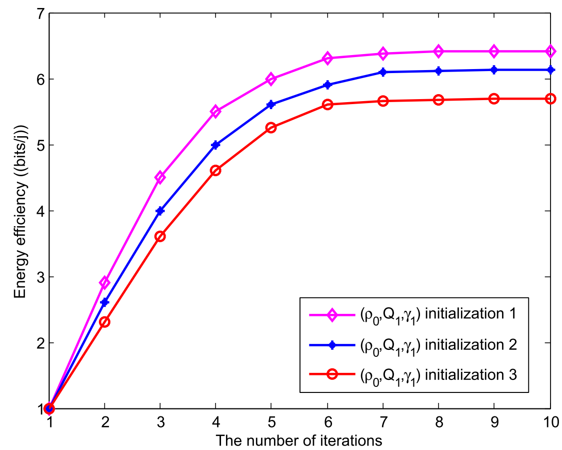


**FIGURE 2. The security energy efficiency versus the iteration number for different initializations of $(\rho_0, \mathbf{Q}_1, \gamma_1)$ with algorithm 2.**

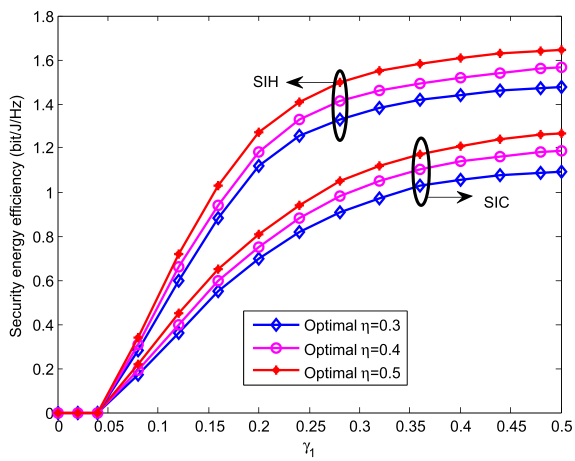


**FIGURE 3. Security energy efficiency vs. transmit power allocation of TWR.**

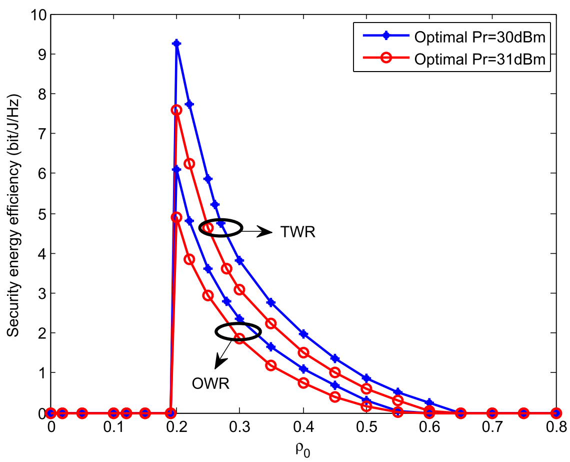


**FIGURE 4.** Security energy efficiency vs. power splitting.

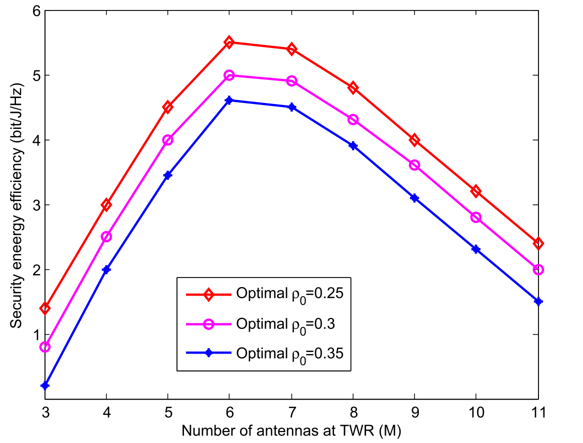


**FIGURE 6.** Security energy efficiency vs. number of transmit antennas at the TWR.

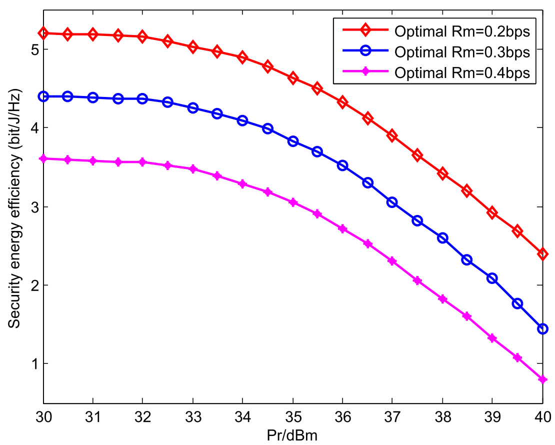


**FIGURE 5.** Security energy efficiency vs. the relay transmit power.

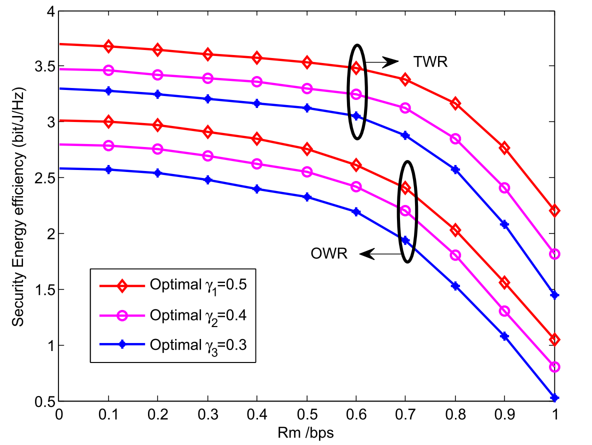


**FIGURE 7.** Security energy efficiency vs. decoding rate of relay.

energy conversion coefficient, the security energy efficiency of self-interference energy harvesting (SIH) is higher than SIC. The season can be explain that SIH reduces the actual energy consumption of cognitive system, which lead to the improvement of security energy efficiency.

Fig.4 shows the security energy efficiency versus the power splitting of TWR with different relay, when $R_m = 0.2bit/s$, $\eta = 0.8, M = 5, E_{min} = 50\mu W$. As can be observed from the figure, the security energy efficiency of the cognitive system is 0 in low power splitting. It is not difficult to understand in order to meet the minimum decoding rate and energy harvest of the relay node, $\rho_0$ must be within a certain range. Moreover, when $0.19 \leq \rho_0 < 0.68$, with the impact level of $\rho_0$ increasing, the security energy efficiency degrades. This is due to the fact that with the increase of $\rho_0$, more received power of TWR is required to meet the decoding rate. So that, less power is allocated to harvest energy, which lead to a lower security energy efficiency. In addition, the security energy efficiency of TWR is superior to the OWR. This is due to the fact that TWR is able to achieve higher rates and harvest more energy values compared to OWR at the same time.

Fig. 5 shows security energy efficiency versus the relay transmit power with different decoding rate of relay, when $\rho_0 = 0.2$, $E_{min} = 50\mu W$, $\eta = 0.5$, $M = 5$. It can be seen from the figure, the security energy efficiency decreases with the transmission power of TWR. It can be readily explained by the fact increasing the transmission power of the SUs will increase the actual energy consumption of the system. In addition, as the decoding rate $R_m$ increases, the security energy efficiency degrades.

Fig.6 depicts the security energy efficiency against the number of transmit antennas at the TWR with various power splitting $\rho_0$, when $R_m = 0.2bit/s$, $\eta = 0.8$, $P_r = 38dBm$, $E_{min} = 50\mu W$. As can be seen, along with the number of the transmit antenna increases, the security energy efficiency firstly increases and then decreases, which is explained by the fact that sufficient transmit antennas can increase the throughput of SUs. It is visible that a higher security energy efficiency is achieved with TWR transmit antenna $N = 6$ than $N > 6$, since more transmit antennas result in increasing circuit power consumption and then degrade the energy efficiency value. Furthermore, we also observed that the security energy efficiency performance decreases with the $\rho_0$ increase, which verifies the analysis in Fig.4.

Fig.7 shows the security energy efficiency versus decoding rate of relay with different relay when $M = 5$, $\eta = 0.8$,

$P_r = 38dBm$, $E_{min} = 50\mu W$. As can be seen that, along with the decoding rate increases, the security energy efficiency decreases. This can be explained as follows, since the relay node can simultaneously receive signal and harvest energy by power allocation. When $R_m$ is large, more received power is required to meet the constraint of decoding rate. Accordingly, less power is allocated to harvest energy, which result in the decrease of security energy efficiency.

## V. CONCLUSION

This paper has investigated the application of TW-FD relay to CR-NOMA system, in which two pairs of users can exchange their information between each other by the TWR. The performance of the CR-NOMA system has been characterized in term of security energy efficiency. In order to enhance the energy efficiency of cognitive system, the self-interference of FD can be regarded as potential source for relay to harvest energy. The semi-determined relaxation algorithm is proposed to solve the non-convex problem. To maximize security energy efficiency, the multi-objective iterative algorithm (MOIA) is proposed to jointly optimize the transmit covariance matrix, power allocation and power splitting ratio. Based on the analytical results, it was shown that the performance of TW-FD with self-interference harvesting outperforms the self-interference cancellation. It also shows that the security energy efficiency of FD-TWR is superior to that of FD-OWR. Moreover, our proposed algorithms can rapidly convergence within few iterations. Next, the physical layer security issue of artificial noise based CR-NOMA system is also the focus of future research.

## APPENDIX A

In order to better distinguish the symbols in the paper, we have tabulated the notations used throughout the manuscript. Please refer to TABLE 4.

## APPENDIX B
## PROOF OF THEOREM 1

*Step one:* For the given $F(\Xi, \lambda) = 0$, one has

$$\frac{\partial F(\Xi, \lambda)}{\partial \lambda} = E_{tot} - P_{tot} < 0 \tag{38}$$

where $\Xi$ denotes the collection of variable $\mathbf{Q}_1$, $\gamma_1$ and $\rho_0$.

Thus, $F(\Xi, \lambda)$ is a decreasing function of $\lambda$ for any $\Xi$. For any $\triangle>0$, we have

$$F(\Xi, \lambda) > F(\Xi, \lambda \dotplus \triangle) \tag{39}$$

Since we have an inequation

$$g(\lambda) = \max_{\Xi} F(\Xi, \lambda) \geq F(\Xi, \lambda) > F(\Xi, \lambda \dotplus \triangle), \quad \forall \Xi \tag{40}$$

it is obtained that

$$g(\lambda) > F(\Xi, \lambda \dotplus \triangle) = g(\lambda \dotplus \triangle) \tag{41}$$

Therefore, $g(\lambda)$ is a decreasing function of $\lambda$.

*Step two:* According to equation (22), one has

$$F(\Xi, f(\Xi)) = 0 \tag{42}$$

where $f(\Xi) = R_{ss}/(P_{tot} - E_{tot})$.

**TABLE 4. Table of parameters for the paper.**

| Parameter description | $Notation$ |
|---|---|
| Receive power allocation of TWR | $\rho_0$ |
| Transmit power allocation of SU | $a_i(i=1,2...,4)$ |
| Transmit power allocation coefficients of TWR | $\gamma_i(i=1,2,...,4)$ |
| Energy conversion efficiency | $\eta$ |
| Transmit signal of TWR | $\mathbf{x}_i(i=1,2)$ |
| Transmit signal of PU | $s_n$ |
| The channel from SU to TWR | $\mathbf{H}_i(i=1,2,3,4)$ |
| The channel from TWR to SU | $\mathbf{H}_{Ri}(i=1,2,3,4)$ |
| Loopback channel of TWR | $\mathbf{H}_{Oi}(i=1,2)$ |
| Transmit signal covariance of $\mathbf{x}_i(i=1,2)$ | $\mathbf{Q}_i(i=1,2)$ |
| Transmit beamforming vector of the TWR | $\mathbf{w}_i(i=1,2,...,4)$ |
| Transmission power at SUs | $p_s$ |
| Transmission power at PT | $p_t$ |
| Transmission power at TWR | $P_r$ |
| Link power consumption of the system | $P_l$ |
| Overall power consumed by the system | $P_{tot}$ |
| The total energy harvested by the TWR | $E_{tot}$ |
| Security energy efficiency of the system | $\eta_{EE}$ |
| Decoding rate of TWR | $R_{Si}(i=1,2)$ |
| Minimum decoding rate of TWR | $R_m$ |
| NOMA minimum successful decoding rate | $R_{th}$ |
| Minimum achievable rate of PR | $R_0$ |
| The rate of $C_1$ to decode the $C_2$ | $R_{1\to 2}$ |
| Security rate of the SU system | $R_S$ |
| Eavesdropping rate of $E_i(i=1,2)$ | $R_e^i(i=1,2)$ |
| The distance between TWR and $C_1$ | $d_1$ |
| The distance between TWR and $C_2$ | $d_2$ |
| The distance between TWR and $C_3$ | $d_3$ |
| The distance between TWR and $C_4$ | $d_4$ |
| Number of antennas of TWR | $M$ |
| Number of antennas of SU | $N$ |

Let $\Xi_{opt}$ be the optimal value of the problem $pro_0$. Since $f\left(\Xi_{opt}\right)$ denotes the maximum of the SEE, $\lambda = f\left(\Xi_{opt}\right)$ is the maximum value of $\lambda$ that meets the constraints of $F(\Xi, \lambda)$.

Defining $\lambda^*$ as the root of $g(\lambda) = 0$, then we have $g(\lambda^*) = 0$ and $\Xi^*$ that can satisfy $F(\Xi, \lambda^*) = 0$. According to the conclusion of Step one, we have

$$g(\lambda_0) = \max_{\Xi} F(\Xi, \lambda_0) < 0 \tag{43}$$

where $\lambda_0 > \lambda^*$.

Since the inequality in (43), the root $\lambda^*$ is the largest value of $F(\Xi, \lambda) = 0$. And we can get $\lambda^* = f\left(\Xi_{opt}\right)$ and $\Xi_{opt} = \Xi^*$. Therefore, the root $\lambda^*$ of $g(\lambda) = 0$ denotes the maximum of the SEE.

## APPENDIX C
## PROOF OF PROPOSITION 1

The objective function is a non-convex due to the existing of the security rate.The Taylor series expansion is proposed to transform the second third and forth items of $R_s$ into the approximate affine function, which is given by

$$\begin{aligned} &\frac{1}{2}\log_2\left|\mathbf{I} + \frac{\xi \mathbf{H}_{R2}\mathbf{Q}_2\mathbf{H}_{R2}^H\gamma_2}{\mathbf{I} + \xi \mathbf{H}_{R2}\mathbf{Q}_1\mathbf{H}_{R2}^H\gamma_1}\right| \\ &= \frac{1}{2}\log_2\left|\mathbf{I} + \frac{\xi \mathbf{H}_{R2}\mathbf{Q}_2\mathbf{H}_{R2}^H\gamma_2}{\mathbf{I} + \xi \mathbf{H}_{R2}\mathbf{Q}_1\mathbf{H}_{R2}^H\gamma_1}\right| \\ &\quad + \frac{1}{2ln2}tr(\mathbf{H}_{R2}^H\Theta_1^{-1}\chi_1\mathbf{H}_{R2}(\mathbf{Q}_1 - \mathbf{Q}_{10})) \end{aligned} \tag{44}$$

$$\begin{aligned}&\frac{1}{2}\log_2\left|\mathbf{I}+\xi\mathbf{H}_{e1}\mathbf{Q}_1\mathbf{H}_{e1}^H\gamma_1\right|\\&=\frac{1}{2}\log_2\left|\mathbf{I}+\xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1\right|\\&\quad+\frac{\xi\gamma_1\rho_0}{2ln2}tr(\mathbf{H}_{e1}^H(\mathbf{I}+\xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1)^{-1}\mathbf{H}_{e1}(\mathbf{Q}_1-\mathbf{Q}_{10}))\end{aligned} \tag{45}$$

$$\begin{aligned}&\frac{1}{2}\log_2\left|\mathbf{I}+\frac{\xi\mathbf{H}_{e1}\mathbf{Q}_2\mathbf{H}_{e1}^H\gamma_2}{\mathbf{I}+\xi\mathbf{H}_{e1}\mathbf{Q}_1\mathbf{H}_{e1}^H\gamma_1}\right|\\&=\frac{1}{2}\log_2\left|\mathbf{I}+\frac{\xi\mathbf{H}_{e1}\mathbf{Q}_2\mathbf{H}_{e1}^H\gamma_2}{\mathbf{I}+\xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1}\right|\\&\quad+\frac{1}{2ln2}tr(\mathbf{H}_{e1}^H\Theta_2^{-1}\chi_2\mathbf{H}_{e1}(\mathbf{Q}_1-\mathbf{Q}_{10}))\end{aligned} \tag{46}$$

each parameter represents $\Theta_1 = (\mathbf{I}+\frac{\xi\mathbf{H}_{R2}\mathbf{Q}_2\mathbf{H}_{R2}^H\gamma_2}{\mathbf{I}+\xi\mathbf{H}_{R2}\mathbf{Q}_{10}\mathbf{H}_{R2}^H\gamma_1})$, $\Theta_2 = (\mathbf{I}+\frac{\xi\mathbf{H}_{e1}\mathbf{Q}_2\mathbf{H}_{e1}^H\gamma_2}{\mathbf{I}+\xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1})$, $\chi_1 = \frac{\xi^2\gamma_1\gamma_2\mathbf{H}_{R2}\mathbf{Q}_2\mathbf{H}_{R2}^H}{(\mathbf{I}+\xi\mathbf{H}_{R2}\mathbf{Q}_{10}\mathbf{H}_{R2}^H\gamma_1)^2}$, $\chi_1 = \frac{\xi^2\gamma_1\gamma_2\mathbf{H}_{e1}\mathbf{Q}_2\mathbf{H}_{e1}^H}{(\mathbf{I}+\xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1)^2}$.

Accordingly, the approximate function of the security rate $R_{ss}$ is obtained by

$$\begin{aligned}R_s^* &= \frac{1}{2}\log\left|\mathbf{I}+\mathbf{H}_{R1}\mathbf{Q}_1\mathbf{H}_{R1}^H\gamma_1\right|\\&\quad+\frac{1}{2ln2}tr(\mathbf{H}_{R2}^H\Theta_1^{-1}\chi_1\mathbf{H}_{R2}\mathbf{Q}_1)\\&\quad-\frac{1}{2ln2}tr(\mathbf{H}_{e1}^H\Theta_2^{-1}\chi_2\mathbf{H}_{e1}\mathbf{Q}_1)\\&\quad-\frac{\xi\gamma_1}{2ln2}tr(\mathbf{H}_{e1}^H(\mathbf{I}+\xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1)^{-1}\mathbf{H}_{e1}\mathbf{Q}_1)+\varphi\end{aligned} \tag{47}$$

where $\varphi = X_1 + X_2 + X_3$, each variable in the formula is represented as

$$\begin{aligned}X_1 &= \frac{1}{2}\log_2\left|\mathbf{I}+\frac{\xi\mathbf{H}_{R2}\mathbf{Q}_2\mathbf{H}_{R2}^H\gamma_2}{\mathbf{I}+\xi\mathbf{H}_{R2}\mathbf{Q}_{10}\mathbf{H}_{R2}^H\gamma_1}\right|\\&\quad-\frac{1}{2ln2}tr(\mathbf{H}_{R2}^H\Theta_1^{-1}\chi_1\mathbf{H}_{R2}\mathbf{Q}_{10})\\X_2 &= \frac{\xi\gamma_1}{2ln2}tr(\mathbf{H}_{e1}^H(\mathbf{I}+\xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1)^{-1}\mathbf{H}_{e1}\mathbf{Q}_{10})\\&\quad-\frac{1}{2}\log_2\left|\mathbf{I}+\xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1\right|\\X_3 &= \frac{1}{2ln2}tr(\mathbf{H}_{e1}^H\Theta_1^{-1}\chi_2\mathbf{H}_{e1}\mathbf{Q}_{10})\\&\quad-\frac{1}{2}\log_2\left|\mathbf{I}+\frac{\xi\mathbf{H}_{e1}\mathbf{Q}_2\mathbf{H}_{e1}^H\gamma_2}{\mathbf{I}+\xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1}\right|\end{aligned}$$

where $\varphi$ is a constant for the given $Q_{10}$.

In accordance with (47), the constraints $R_P$ and $R_{1\to 2}$ can be rewritten by.

$$\begin{aligned}R_P^* &= \frac{1}{2}\log_2(2\mathbf{h}_{RP}(\mathbf{Q}_1+\mathbf{Q}_2)\mathbf{h}_{RP}^H+\delta^2+p_t+p_t\mathbf{H}_{pp})\\&\quad-\frac{\mathbf{h}_{RP}\mathbf{h}_{RP}^H\mathbf{Q}_1}{ln2(2\mathbf{h}_{RP}(\mathbf{Q}_{10}+\mathbf{Q}_2)\mathbf{h}_{RP}^H+\delta_P^2)}+\varphi_1\end{aligned} \tag{48}$$

$$R_{1\to 2}^* = \frac{tr\left(\mathbf{H}_{R1}\frac{\xi^2\mathbf{H}_{R1}\mathbf{Q}_2\mathbf{H}_{R1}^H\gamma_2\gamma_1}{(\mathbf{I}+\xi\mathbf{H}_{R1}\mathbf{Q}_{10}\mathbf{H}_{R1}^H\gamma_1)^2}\mathbf{H}_{R1}\mathbf{Q}_1\right)}{2ln2}+\varphi_2 \tag{49}$$

where

$$\begin{aligned}\varphi_1 &= \frac{\mathbf{h}_{RP}\mathbf{h}_{RP}^H\mathbf{Q}_{10}}{ln2\left(2\mathbf{h}_{RP}\left(\mathbf{Q}_{10}+\mathbf{Q}_2\right)\mathbf{h}_{RP}^H+\sigma_P^2\right)}\\&\quad-\frac{1}{2}\log_2(2\mathbf{h}_{RP}(\mathbf{Q}_{10}+\mathbf{Q}_2)\mathbf{h}_{RP}^H+\sigma_P^2+p_t\mathbf{H}_{PP})\\\varphi_2 &= \frac{1}{2}\log_2\left|\mathbf{I}+\frac{\xi\mathbf{H}_{R1}\mathbf{Q}_2\mathbf{H}_{R2}^H\gamma_2}{\mathbf{I}+\xi\mathbf{H}_{R1}\mathbf{Q}_{10}\mathbf{H}_{R1}^H\gamma_2}\right|\\&\quad-\frac{1}{2ln2}tr\left(\mathbf{H}_{R1}^H\frac{\xi^2\mathbf{H}_{R1}\mathbf{Q}_2\mathbf{H}_{R1}^H\gamma_2\gamma_1}{(\mathbf{I}+\xi\mathbf{H}_{R1}\mathbf{Q}_{10}\mathbf{H}_{R1}^H\gamma_1)^2}\mathbf{H}_{R1}\mathbf{Q}_{10}\right)\end{aligned}$$

where, $\varphi_1$ and $\varphi_2$ are constants for the given $Q_{10}$.

## APPENDIX D
## PROOF OF THEOREM 2

According to the performance of trace operation that $tr(\mathbf{CD}) = tr(\mathbf{DC})$, we can get $tr(\Psi\mathbf{Q}) = tr(\Psi^{\frac{1}{2}}\mathbf{Q}\Psi^{\frac{1}{2}})$. Then, a new auxiliary variable is defined as

$$\mathbf{Q}^r = \Psi^{\frac{1}{2}}\mathbf{Q}\Psi^{\frac{1}{2}} \tag{50}$$

Plugging the (50) into (28), we have

$$\begin{aligned}&\lambda(P_{tot}-E_{tot})-[\frac{1}{2}\log\left|\mathbf{I}+(\mathbf{H}_{R1}\Psi_1^{-\frac{1}{2}})\mathbf{Q}_1^r(\mathbf{H}_{R1}\Psi_1^{-\frac{1}{2}})^H\gamma_1\right|\\&+\frac{1}{2ln2}tr(\mathbf{H}_{R2}^H\Theta_1^{-1}\chi_1\mathbf{H}_{R2}\mathbf{Q}_1^r)\\&-\frac{1}{2ln2}tr(\mathbf{H}_{e1}^H\Theta_2^{-1}\chi_2\mathbf{H}_{e1}\mathbf{Q}_1^r)\\&-\frac{\xi\gamma_1}{2ln2}tr(\mathbf{H}_{e1}^H(\mathbf{I}+\xi\mathbf{H}_{e1}\mathbf{Q}_{10}\mathbf{H}_{e1}^H\gamma_1)^{-1}\mathbf{H}_{e1}\mathbf{Q}_1^r)+\varphi]\end{aligned} \tag{51}$$

The right singular vectors $\mathbf{V}_1$ is given by the SVD of the $\mathbf{H}_{R1}\Psi^{-\frac{1}{2}}$.

$$\mathbf{H}_{R1}\Psi_1^{-\frac{1}{2}} = \mathbf{U}_1\Lambda\mathbf{V}_1^H \tag{52}$$

The optimum solution to the transmit covariance are obtained through the Hadamard inequality, and the closed-form expression are given by

$$\mathbf{Q}_1^{r*} = \mathbf{V}_1\Delta\mathbf{V}_1^H \tag{53}$$

According to the equation (50), the optimum of the transmission covariance are reformulated as

$$\mathbf{Q}_1^* = \Psi_1^{-\frac{1}{2}}\mathbf{V}_1\Delta\mathbf{V}_1^H\Psi_1^{-\frac{1}{2}} \tag{54}$$

## REFERENCES

[1] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, "What will 5G be?" *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1065–1082, Jun. 2014.
[2] Z. Zhang, H. Sun, and R. Q. Hu, "Downlink and uplink non-orthogonal multiple access in a dense wireless network," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 12, pp. 115–117, Dec. 2017.
[3] Z. Ding, X. Lei, G. K. Karagiannidis, R. Schober, J. Yuan, and V. Bhargava, "A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2181–2195, Oct. 2017.
[4] B. Wang, L. Dai, Z. Wang, N. Ge, and S. Zhou, "Spectrum and energy efficient beamspace MIMO-NOMA for millimeter-wave communications using lens antenna array," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2370–2382, Oct. 2017.

[5] X. Xu, W. Yang, Y. Cai, and S. Jin, "On the secure spectral-energy efficiency tradeoff in random cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 10, pp. 2706–2722, Oct. 2016.
[6] Y. Liu, Z. Ding, M. Elkashlan, and J. Yuan, "Nonorthogonal multiple access in large-scale underlay cognitive radio networks," *IEEE Trans. Veh. Tech.*, vol. 65, no. 12, pp. 10152–10157, Dec. 2016.
[7] F. Zhou, Y. Wu, Y.-C. Liang, Z. Li, Y. Wang, and K.-K. Wong, "State of the art, taxonomy, and open issues on cognitive radio networks with NOMA," *IEEE Wireless Commun.*, vol. 25, no. 2, pp. 100–108, Apr. 2018.
[8] S. Arzykulov, T. A. Tsiftsis, G. Nauryzbayev, and M. Abdallah, "Outage performance of cooperative underlay CR-NOMA with imperfect CSI," *IEEE Commun. Lett.*, vol. 23, no. 1, pp. 176–179, Jan. 2019.
[9] M. Mohammadi, B. K. Chalise, A. Hakimi, Z. Mobini, H. A. Suraweera, and Z. Ding, "Beamforming design and power allocation for full-duplex non-orthogonal multiple access cognitive relaying," *IEEE Trans. Commun.*, vol. 66, no. 12, pp. 5952–5965, Dec. 2018.
[10] S. M. Kim and J. Kim, "Virtual full-duplex relay selection in relay-assisted cognitive radio networks," in *Proc. 9th Int. Conf. Ubiquitous Future Netw. (ICUFN)*, Milan, Italy, Jul. 2017, pp. 1–6.
[11] X. Yue, Y. Liu, S. Kang, A. Nallanathan, and Z. Ding, "Exploiting full/half-duplex user relaying in NOMA systems," *IEEE Trans. Commun.*, vol. 66, no. 2, pp. 560–575, Feb. 2018.
[12] H. Huang, J. Xiong, J. Yang, G. Gui, and H. Sari, "Rate region analysis in a full-duplex-aided cooperative nonorthogonal multiple-access system," *IEEE Access*, vol. 5, pp. 17869–17880, 2017.
[13] B. Xia, C. Li, and Q. Jiang, "Outage performance analysis of multi-user selection for two-way full-duplex relay systems," *IEEE Commun. Lett.*, vol. 21, no. 4, pp. 933–936, Apr. 2017.
[14] Y. Li, N. Li, H. Li, W. Xie, M. Wang, and M. Peng, "Spectrum sharing based on overlay cognitive full-duplex two-way OFDM relaying: Protocol design and resource allocation," *IEEE Trans. Vel. Technol.*, vol. 67, no. 3, pp. 2324–2334, Mar. 2018.
[15] B. Zhong and Z. Zhang, "Opportunistic two-way full-duplex relay selection in underlay cognitive networks," *IEEE Syst. J.*, vol. 12, no. 1, pp. 725–734, Mar. 2018.
[16] D. E. Simmons and J. P. Coon, "Two-way OFDM-based nonlinear amplify-and-forward relay systems," *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3808–3812, May 2016.
[17] S. H. Safavi, M. Ardebilipour, and S. Salari, "Relay beamforming in cognitive two-way networks with imperfect channel state information," *IEEE Wireless Commun.*, vol. 1, no. 4, pp. 344–347, Aug. 2012.
[18] A. H. Bastami and S. Habibi, "Cognitive MIMO two-way relay network: Joint optimal relay selection and spectrum allocation," *IEEE Trans. Vel. Technol.*, vol. 67, no. 7, pp. 5937–5952, Jul. 2018.
[19] B. Zheng, X. Wang, M. Wen, and F. Chen, "NOMA-based multi-pair two-way relay networks with rate splitting and group decoding," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2328–2341, Oct. 2017.
[20] X. Yue, Y. Liu, S. Kang, A. Nallanathan, and Y. Chen, "Modeling and analysis of two-way relay non-orthogonal multiple access systems," *IEEE Trans. Commun.*, vol. 66, no. 9, pp. 3784–3796, Sep. 2018.
[21] T. Riihonen, S. Werner, and R. Wichman, "Hybrid full-duplex/half-duplex relaying with transmit power adaptation," *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 3074–3085, Sep. 2011.
[22] Y. Gao, H. He, Z. Deng, and X. Zhang, "Cognitive radio network with energy-harvesting based on primary and secondary user signals," *IEEE Access*, vol. 6, pp. 9081–9090, 2018.
[23] Z. Hu, C. Yuan, and F. Gao, "Maximizing harvested energy for full-duplex SWIPT system with power splitting," *IEEE Access*, vol. 5, pp. 24975–24987, 2017.
[24] D. Wang, R. Zhang, X. Cheng, L. Yang, and C. Chen, "Relay selection in full-duplex energy-harvesting two-way relay networks," *IEEE Trans. Green Commun. Netw.*, vol. 1, no. 2, pp. 182–191, Jun. 2017.
[25] M. R. Amini, M. Mahdavi, and M. J. Omidi, "Energy efficiency optimization of secondary network considering primary user return with alternating-phase-type traffic," *IEEE Trans. Commun.*, vol. 65, no. 7, pp. 3095–3109, Jul. 2017.
[26] Y. Wu, R. Schober, D. W. K. Ng, C. Xiao, and G. Caire, "Secure massive MIMO transmission with an active eavesdropper," *IEEE Trans. Inf. Theory*, vol. 62, no. 7, pp. 3880–3900, Jul. 2016.
[27] Y. Zhang, H.-M. Wang, Q. Yang, and Z. Ding, "Secrecy sum rate maximization in non-orthogonal multiple access," *IEEE Commun. Lett.*, vol. 20, no. 5, pp. 930–933, May 2016.
[28] Y. Li, M. Jiang, Q. Zhang, Q. Li, and J. Qin, "Secure beamforming in downlink MISO nonorthogonal multiple access systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 7563–7567, Aug. 2017.
[29] H. Lei, J. Zhang, K.-H. Park, P. Xu, I. S. Ansari, G. Pan, B. Alomairi, and M.-S. Alouini, "On secure NOMA systems with transmit antenna selection schemes," *IEEE Access*, vol. 5, pp. 17450–17464, 2017.
[30] B. He, A. Liu, N. Yang, and V. K. N. Lau, "On the design of secure non-orthogonal multiple access systems," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2196–2206, Oct. 2017.
[31] M. Tian, Q. Zhang, S. Zhao, Q. Li, and J. Qin, "Secrecy sum rate optimization for downlink MIMO nonorthogonal multiple access systems," *IEEE Signal Process. Lett.*, vol. 24, no. 8, pp. 1113–1117, Aug. 2017.
[32] X. Xu, W. Yang, and Y. Cai, "Opportunistic relay selection improves reliability-reliability tradeoff and security-reliability tradeoff in random cognitive radio networks," *IET Commun.*, vol. 11, no. 3, pp. 335–343, Feb. 2017.
[33] N. Nandan, S. Majhi, and H.-C. Wu, "Secure beamforming for MIMO-NOMA-based cognitive radio network," *IEEE Commun. Lett.*, vol. 22, no. 8, pp. 1708–1711, Aug. 2018.
[34] L. Xu, A. Nallanathan, X. Pan, J. Yang, and W. Liao, "Security-aware resource allocation with delay constraint for NOMA-based cognitive radio network," , vol. 13, no. 2, pp. 366–376, Feb. 2018.
[35] F. Zhou, Z. Chu, H. Sun, R. Q. Hu, and L. Hanzo, "Artificial noise aided secure cognitive beamforming for cooperative MISO-NOMA using SWIPT," *IEEE Trans. J. Sel. Areas. Commum.*, vol. 36, no. 4, pp. 918–931, Apr. 2018.
[36] Y. Jiang, Y. Zou, J. Ouyang, and J. Zhu, "Secrecy energy efficiency optimization for artificial noise aided physical-layer security in OFDM-based cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 12, pp. 11858–11872, Dec. 2018.

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