Secure Massive MIMO System with Two-Way Relay Cooperative Transmission in 6G Networks

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1   **Secure Massive MIMO System with Two-Way Relay** 2   **Cooperative Transmission in 6G Networks**

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6   **Abstract** With the advent of Internet of Everything (IoE) and the era of big data,
7   massive multiple-input multiple-output (MIMO) is considered an essential technology
8   to meet the growing communication requirements for beyond 5G and the forthcoming
9   6G networks. This paper considers a secure massive MIMO system, where the
10   legitimate user and the base station (BS) exchange messages via two-way relays with
11   the presence of passive eavesdroppers. To achieve the trade-off between the
12   physical-layer security and communication reliability, we design a cooperative
13   transmission mode based on multiple-relay collaboration, where some relays
14   broadcast the received signals and other relays act as friendly jammers to prevent the
15   interception by eavesdroppers. A quantum chemical reaction optimization (QCRO)
16   algorithm is proposed to find the most suitable scheme for multiple-relay
17   collaboration. Simulation results highlight excellent performance of the proposed
18   transmission mode under QCRO in different communication scenarios, which can be
19   considered a potential solution for the security issue in future wireless networks.

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21   **Keywords:** 6G, physical-layer security, massive MIMO, multiple-relay collaboration,
22   two-way relaying

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1 Introduction

In contemporary society, as the booming development of information technology and the popularity of intelligent equipment, wireless networks have become an essential part of our daily life [1]. Inheriting the benefits achieved in 5G, 6G network is expected to expand to a wider level to realize the full coverage of land and air [2-5]. As networks become denser, how to efficiently utilize the system resources and how to meet the higher transmission demands of ultra-high speed, high quality, and low latency have becoming key topics in 6G networks [3-5]. Massive MIMO is an effective solution for the increasing challenge of wireless data traffic since it can serve a large number of IoT devices at the same time [6-9]. By utilizing large antenna arrays, massive MIMO system can transmit several directional beams to the desired terminals, which can greatly improve the quality of service (QoS) and spectral efficiency of communication systems [10].

Due to the openness of transmission environments and the broadcast nature of wireless channels, secure transmission has becoming a critical issue in wireless networks [11, 12]. Since eavesdroppers will make every effort to intercept or break the information transmission, many scholars have conducted in-depth research on how to protect the transmission of confidential information. Typically, cryptographic encryption method was used to maintain the system privacy [13-15]. However, the implementation complexity is too high due to the cumbersome process of service management. By exploiting wireless transmission properties, physical-layer security has attracted considerable attentions in massive MIMO networks [16, 17]. Several efforts such as artificial noise [18-20], antenna/relay selection [21-23], and cooperative strategies [24-27] have been employed to deal with the information leakage by eavesdroppers. The utilization of antenna correlation diversity was

demonstrated to improve the secrecy rate of massive MIMO systems [19]. With the assistance of cooperative relays, the authors in [24] and [25] investigated the secure transmission problem in the presence of passive and active eavesdroppers. Hoang *et al.* [26] investigated the secrecy performance under a practical scenario where the eavesdroppers hide their existence in the system. In [21], Kuhestani *et al.* considered the scenario in a cooperative massive MIMO relay network where untrusted relays act as potential eavesdroppers. A destination-based cooperative jamming is implemented to improve the system capacity and transmission confidentiality.

Among recent works on the security issue, the combinations of cooperative relays and secure techniques have shown significant improvements on secrecy capacity and system coverage. Due to the low-complexity relaying process and high spectral efficiency outperforms one-way relay network, two-way relays have attracted extensive attentions [28-31]. In two-way relay networks, eavesdroppers receive the overlapped information when the two legitimate devices broadcast their signals at the same time [31]. In this condition, both two devices act as source and jammer to prevent the interception by eavesdroppers. By exploiting the dual property, the authors in [32] and [33] investigated distributed relay selection criterion to optimize the system security performance. In order to enhance the spatial diversity gains and further improve the system performance, massive MIMO with two-way relay collaboration has become a hotspot in recent researches [34-37]. In [35], Feng *et al.* indicated that the system performance with full-duplex operation outperforms the half-duplex mode under a certain self-loop interference. Zhang *et al.* [36] investigated the overall performance with hardware impairments. In [37], Pan *et al.* adopted a power allocation strategy based on geometric programming to reduce the information interception of untrusted users. These works, however, did not consider the

information leakage happens at the two phases of data transmission.

1.1 Motivation and contributions

Table 1 Comparison with existing works

Reference	Category	Power allocation	Security strategy	Cooperative communication	Multiple-relay selection	Using duality
[16]-[20]	DT	✓	✓	×	×	×
[21]	OWR	✓	✓	✓	×	×
[22]	OWR	×	×	✓	×	×
[23]	OWR	✓	✓	✓	✓	×
[24]	OWR	✓	×	✓	×	×
[25]-[27]	OWR	✓	✓	✓	×	×
[28]	TWR	×	×	✓	×	×
[29]	TWR	✓	×	✓	×	×
[30]	TWR	✓	✓	✓	×	✓
[31]	TWR	×	✓	✓	×	×
[32, 33]	TWR	×	×	✓	×	✓
[37]	TWR	✓	×	✓	×	✓
Our work	TWR	✓	✓	✓	✓	✓

(DT: Direct transmission   OWR: One-way relaying   TWR: Two-way relaying)

Although existing researches have made influential achievements in improving the security performance, there are still some limitations. For better understanding, the comparison of previous works with our work is presented in **Table 1**. Many anti-eavesdropping methods [16-20] generally consider the case of direct transmission between the BS and the users, but it's hard to meet the QoS demands of the desired terminals where there are no direct transmission links due to the long-distance fading. For secure transmission issues with relay collaboration, most of the existing works [21-33, 37] do not simultaneously address the power allocation, resource utilization, and multiple relay selection in a scenario where information leakage happens at both transmission phases in massive MIMO networks with limited time-frequency resources. In this paper, we present a cooperative transmission mode for the security

issue of massive MIMO two-way relay networks. Unlike one-way relaying systems, both the two legitimate devices play the roles of source and jammer via two-way relaying operation. However, the duality has not been well exploited in [28, 29, 31] to prevent the interception by eavesdroppers. In order to break through the limitations of previous studies and obtain a higher security performance, we propose a multiple-relay collaboration strategy considering the interception of eavesdroppers during the two phases of information transmission. According to the multiple-relay selection (MRS) scheme, the relays function as receivers/transmitters or friendly jammers to reduce the information leakage between the source and the legitimate user. Considering the energy conservation and communication reliability requirements, we propose a quantum chemical reaction optimization (QCRO) algorithm to obtain the optimal MRS result. The major contributions of our work are summarized in the following:

- We present a low-complexity cooperative transmission mode to balance the communication security and reliability of a massive MIMO two-way relay system. A multiple-relay collaboration strategy is employed to enhance the secrecy performance while prevent the interception by eavesdroppers in two transmission phases.
- Exact expression for secrecy sum-rate is derived considering the information leakage of two transmission phases in massive MIMO relay networks. The expression indicates that secrecy performance is affected by the transmission power of relays and MRS result with QoS and interference constraints in practical scenarios.
- A novel algorithm named QCRO is proposed to tackle the complicated MRS problem for the cooperative transmission in massive MIMO networks.

Simulation results illustrate the excellent performance of QCRO over conventional algorithms in various system parameters. Besides, the proposed QCRO algorithm can be considered as a potential solution for other complicated problems in communication domain.

1.2 Organization and notations

The other sections of this work are presented as follows. Section 2 presents the system architecture and the analysis of a secure massive MIMO network with multiple-relay collaboration. The QCRO algorithm for MRS is addressed in Section 3, and Section 4 presents the simulations. In the end, we conclude this work in the final section.

Notations: The uppercase boldface symbols and lowercase boldface symbols represent matrixes and the vectors, respectively. $\mathbf{0}$ and $\mathbf{I}_N$ represent the zero vector and identity matrix, respectively. $\text{CN}(\mu, \sigma^2)$ denotes the complex Gaussian distribution with mean of μ and variance of σ^2 . $(\cdot)^T$ and $(\cdot)^H$ represent transpose operator and conjugate transpose operator, respectively. $|\cdot|$, $\|\cdot\|$, and $\text{abs}(\cdot)$ represent modulus, Euclidean norm, and absolute value functions, respectively. $E\{\cdot\}$ denotes the statistical expectation, and $[x]^+$ stands for $\max\{0, x\}$.

2 System model

In this paper, we introduce a secure massive MIMO system where there is a BS with M_t antennas, a user, L relays, and K eavesdroppers. The BS and the user exchange their information via two-way relay networks, and each eavesdropper tries to intercept the desired signals during the two phases of transmission. Regarding propagation model, the channel state information (CSI) is defined as $\mathbf{g}_{X,Y} = \mathbf{h}_{X,Y} d_{X,Y}^{-\xi/2}$

[26], where $\mathbf{h}_{X,Y} \sim \text{CN}(\mathbf{0}, \mathbf{I}_N)$ denotes the small-scale fading factor, and $d_{X,Y}^{-\xi/2}$ denotes the large-scale fading factor. In it, ξ denotes the path loss exponent, and $d_{X,Y}$ denotes the distance between the X–Y link. The global CSI is available by uplink training in time-division duplexed (TDD) massive MIMO networks [11, 38]. We consider the instantaneous CSI remains unchanged in one time slot. The definitions of CSI between the terminals of secure massive MIMO two-way relay networks are as follows:

- CSI from the BS to the i -th relay: $\mathbf{g}_{BS,r_i}$
- CSI from the BS to the k -th eavesdropper: $\mathbf{g}_{BS,e_k}$
- CSI from the user to the k -th eavesdropper: $\mathbf{g}_{u,e_k}$
- CSI from the i -th relay to the user: $\mathbf{g}_{r_i,u}$
- CSI from the i -th relay to the k -th eavesdropper: $\mathbf{g}_{r_i,e_k}$
- CSI from the i -th relay to the j -th relay ($i \neq j$): $\mathbf{g}_{r_i,r_j}$

In the following, we introduce the cooperative transmission mode with cooperative relaying and cooperative jamming (CRCJ) for the secure massive MIMO two-way relay network.

2.1 CRCJ policy

Since the direct transmission link between the BS and the user is so weak due to the long-distance fading, we consider a scenario where the BS and the user exchange their desired signals via two-way relays. In this system, the BS and the user broadcast their signals with transmit power p_{BS} and p_u . Under CRCJ policy, some relays are selected to receive the mixed signal from the BS and the user, while the remaining relays act as jammers to transmit jamming signals to prevent the information

interception by eavesdroppers. For simplicity, the MRS scheme is expressed by a binary vector $\mathbf{b}=[b_1, b_2, \dots, b_L]$, where $b_i \in \{0, 1\}$, $i=1, 2, \dots, L$. If $b_i=1$, the i -th relay is selected to assist information transmission between the legitimate devices. The signal received at the i -th relay is given by

$$y_i = \sqrt{p_{BS}} \mathbf{g}_{BS, \hat{r}_i} \mathbf{V} s_{BS} + \sqrt{p_u} g_{\hat{r}_i, u} s_u + \sum_{j=1}^L (1-b_j) \sqrt{p_{r_j}} g_{\hat{r}_i, r_j} s_{r_j} + \eta_{\hat{r}_i} \quad (1)$$

where p_{r_j} is the transmit power of the j -th jammer; $\mathbf{V}$ is the precoding matrix at the BS; s_{BS} , s_u , and s_{r_j} are unit-power signals with $E\{\|s_{BS}\|^2\}=1$, $E\{|s_u|^2\}=1$, and $E\{|s_{r_j}|^2\}=1$, respectively; $\eta_{\hat{r}_i}$ is the additive white Gaussian noise (AWGN).

For the k -th eavesdropper, the intercepted signal in the first phase can be expressed as

$$y_{e_k}^{(1)} = \sqrt{p_{BS}} \mathbf{g}_{BS, e_k} \mathbf{V} s_{BS} + \sqrt{p_u} g_{u, e_k} s_u + \sum_{j=1}^L (1-b_j) \sqrt{p_{r_j}} g_{r_j, e_k} s_{r_j} + \eta_{e_k}^{(1)} \quad (2)$$

where $\eta_{e_k}^{(1)}$ is the AWGN. The signal-to-interference plus noise ratio (SINR) received at the k -th eavesdropper from the two legitimate devices (BS and user) can be respectively given by

$$\gamma_{BS \rightarrow e_k}^{(1)} = \frac{p_{BS} \|\mathbf{g}_{BS, e_k} \mathbf{V}\|^2}{p_u |g_{u, e_k}|^2 + \sum_{j=1}^L (1-b_j) p_{r_j} |g_{r_j, e_k}|^2 + \sigma_0^2} \quad (3)$$

$$\gamma_{u \rightarrow e_k}^{(1)} = \frac{p_u |g_{u, e_k}|^2}{p_{BS} \|\mathbf{g}_{BS, e_k} \mathbf{V}\|^2 + \sum_{j=1}^L (1-b_j) p_{r_j} |g_{r_j, e_k}|^2 + \sigma_0^2} \quad (4)$$

where σ_0^2 denotes the power of AWGN.

In the second phase of data transmission, the selected relay i broadcast the

177 normalized signal to the legitimate devices with the transmit power of p_i . The
 178 normalized transmission signal is denoted as

$$179 \quad y_i^{\text{norm}} = \sqrt{G_i} y_i = \frac{y_i}{\sqrt{p_{BS} \|\mathbf{g}_{BS,r_i} \mathbf{V}\|^2 + p_u |g_{r_i,u}|^2 + \sum_{j=1}^L (1-b_j) p_{r_j} |g_{r_i,r_j}|^2 + \sigma_0^2}} \quad (5)$$

180 where $G_i = \left(p_{BS} \|\mathbf{g}_{BS,r_i} \mathbf{V}\|^2 + p_u |g_{r_i,u}|^2 + \sum_{j=1}^L (1-b_j) p_{r_j} |g_{r_i,r_j}|^2 + \sigma_0^2 \right)^{-1}$ is the
 181 normalization factor. After self-interference cancellation (SIC), the corresponding
 182 signals at the BS and the user can be respectively expressed by

$$183 \quad \mathbf{y}_{BS} = \sum_{i=1}^L b_i \sqrt{G_i p_i} \mathbf{W} \mathbf{g}_{BS,r_i}^T \cdot \left(\sqrt{p_u} g_{r_i,u} s_u + \sum_{j=1}^L (1-b_j) \sqrt{p_{r_j}} g_{r_i,r_j} s_{r_j} + \eta_{r_i} \right) + \eta_{BS} \quad (6)$$

184 and

$$185 \quad y_u = \sum_{i=1}^L b_i \sqrt{G_i p_i} g_{r_i,u} \cdot \left(\sqrt{p_{BS}} \mathbf{g}_{BS,r_i} \mathbf{V} s_{BS} + \sum_{j=1}^L (1-b_j) \sqrt{p_{r_j}} g_{r_i,r_j} s_{r_j} + \eta_{r_i} \right) + \eta_u \quad (7)$$

186 where $\mathbf{W}$ is the receiving matrix at the BS; η_{BS} and η_u are AWGN. The SINRs of
 187 the BS and the user are respectively shown by

$$188 \quad \gamma_{u \rightarrow BS} = \frac{\sum_{i=1}^L b_i G_i p_i p_u \|\mathbf{W} \mathbf{g}_{BS,r_i}^T\|^2 \cdot |g_{r_i,u}|^2}{\sum_{i=1}^L \left[b_i G_i p_i \|\mathbf{W} \mathbf{g}_{BS,r_i}^T\|^2 \cdot \left(\sum_{j=1}^L (1-b_j) p_{r_j} |g_{r_i,r_j}|^2 + \sigma_0^2 \right) \right] + \sigma_0^2} \quad (8)$$

189 and

$$190 \quad \gamma_{BS \rightarrow u} = \frac{\sum_{i=1}^L b_i G_i p_i p_{BS} |g_{r_i,u}|^2 \cdot \|\mathbf{g}_{BS,r_i} \mathbf{V}\|^2}{\sum_{i=1}^L \left[b_i G_i p_i |g_{r_i,u}|^2 \cdot \left(\sum_{j=1}^L (1-b_j) p_{r_j} |g_{r_i,r_j}|^2 + \sigma_0^2 \right) \right] + \sigma_0^2} \quad (9)$$

191 Then, the instantaneous transmission rates of the BS and the user are respectively

192 given by

$$193 \quad C_{BS \rightarrow u} = \frac{1}{2} \log_2(1 + \gamma_{BS \rightarrow u}) \quad (10)$$

194 and

$$195 \quad C_{u \rightarrow BS} = \frac{1}{2} \log_2(1 + \gamma_{u \rightarrow BS}) \quad (11)$$

196 Without the knowledge of the CSI between the legitimate devices and cooperative
 197 relays, the eavesdroppers cannot distinguish the information from the BS and the user.
 198 For the k -th eavesdropper, the intercepted signal in the second phase can be given by

$$199 \quad y_{e_k}^{(2)} = \sum_{i=1}^L b_i \sqrt{G_i p_i} g_{r_i, e_k} y_i + \eta_{e_k}^{(2)} \\
= \sum_{i=1}^L b_i \sqrt{G_i p_i} g_{r_i, e_k} \cdot \left(\sqrt{p_{BS}} \mathbf{g}_{BS, r_i} \mathbf{V} s_{BS} + \sqrt{p_u} g_{r_i, u} s_u + \sum_{j=1}^L (1-b_j) \sqrt{p_{r_j}} g_{r_i, r_j} s_{r_j} + \eta_{r_i} \right) + \eta_{e_k}^{(2)} \quad (12)$$

200 where $\eta_{e_k}^{(2)}$ is the AWGN. The SINR received at the k -th eavesdropper from the BS
 201 and the user can be respectively shown by

$$202 \quad \gamma_{BS \rightarrow e_k}^{(2)} = \frac{\sum_{i=1}^L b_i G_i p_i p_{BS} |g_{r_i, e_k}|^2 \cdot \|\mathbf{g}_{BS, r_i} \mathbf{V}\|^2}{\sum_{i=1}^L \left[b_i G_i p_i |g_{r_i, e_k}|^2 \cdot \left(p_u |g_{r_i, u}|^2 + \sum_{j=1}^L (1-b_j) p_{r_j} |g_{r_i, r_j}|^2 + \sigma_0^2 \right) \right] + \sigma_0^2} \quad (13)$$

$$203 \quad \gamma_{u \rightarrow e_k}^{(2)} = \frac{\sum_{i=1}^L b_i G_i p_i p_u |g_{r_i, e_k}|^2 \cdot |g_{r_i, u}|^2}{\sum_{i=1}^L \left[b_i G_i p_i |g_{r_i, e_k}|^2 \cdot \left(p_{BS} \|\mathbf{g}_{BS, r_i} \mathbf{V}\|^2 + \sum_{j=1}^L (1-b_j) p_{r_j} |g_{r_i, r_j}|^2 + \sigma_0^2 \right) \right] + \sigma_0^2} \quad (14)$$

204 Assuming that the eavesdroppers are independent of each other, the total received
 205 SINR at the passive eavesdroppers from the BS and the user can be respectively given
 206 by

$$\gamma_{BS}^E = \max_{k \in \{1,2,\dots,K\}} \{\gamma_{BS \rightarrow e_k}^{(1)}, \gamma_{BS \rightarrow e_k}^{(2)}\} \quad (15)$$

$$\gamma_u^E = \max_{k \in \{1,2,\dots,K\}} \{\gamma_{u \rightarrow e_k}^{(1)}, \gamma_{u \rightarrow e_k}^{(2)}\} \quad (16)$$

The information leakage from the BS and the user are respectively shown by

$$C_{BS}^E = \frac{1}{2} \log_2(1 + \gamma_{BS}^E) \quad (17)$$

$$C_u^E = \frac{1}{2} \log_2(1 + \gamma_u^E) \quad (18)$$

Hence, the secrecy transmission rates of the BS and the user can be given by

$$C_{BS \rightarrow u}^S = [C_{BS \rightarrow u} - C_{BS}^E]^+ \quad (19)$$

$$C_{u \rightarrow BS}^S = [C_{u \rightarrow BS} - C_u^E]^+ \quad (20)$$

Finally, the secrecy sum-rate can be expressed by

$$C_{\text{sum}} = [C_{BS \rightarrow u} - C_{BS}^E]^+ + [C_{u \rightarrow BS} - C_u^E]^+ \quad (21)$$

2.2 Problem formulation

Based on the CRCJ policy, the problem of secrecy sum-rate maximization based on MRS is formulated as

$$\max C_{\text{sum}}(\mathbf{b}) = \max \{ [C_{BS \rightarrow u}(\mathbf{b}) - C_{BS}^E(\mathbf{b})]^+ + [C_{u \rightarrow BS}(\mathbf{b}) - C_u^E(\mathbf{b})]^+ \} \quad (22a)$$

subject to

$$b_i \in \{0,1\} \quad \forall i \in \{1,2,\dots,L\} \quad (22b)$$

$$\sum_{i=1}^L b_i \geq 1 \quad (22c)$$

$$0 \leq p_i, p_{r_j} \leq p_{\max} \quad \forall i, j \in \{1,2,\dots,L\} \quad (22d)$$

$$\sum_{i=1}^L \left[b_i G_i p_i |g_{r_i, u}|^2 \cdot \left(\sum_{j=1}^L (1-b_j) p_{r_j} |g_{r_i, r_j}|^2 \right) \right] \leq \text{Interference} \quad (22e)$$

$$\sum_{i=1}^L \left[b_i G_i p_i \|\mathbf{W} \mathbf{g}_{BS, r_i}^T\|^2 \cdot \left(\sum_{j=1}^L (1-b_j) p_{r_j} |g_{r_i, r_j}|^2 \right) \right] \leq \text{Interference} \quad (22f)$$

where $P_{\max}$ denotes the maximum transmission power of relays. The relay selection constraints are shown in (22b) and (22c), where (22b) indicates that each relay acts as a jammer or a cooperator to participate in transmission, and (22c) indicates that at least one relay is selected to broadcast confidential signals to the legitimate devices. (22d) denotes the power constraints of cooperative relays and cooperative jammers. (22e) and (22f) are interference constraints of the BS and the user. Due to the receive-and-forward mechanism of two-way relays, the jamming signals transmitted to eavesdroppers can also cause interference to the BS and the legitimate user. Hence, to guarantee the system communication quality, the interference from the cooperative jammers should not exceed the maximum interference threshold I_{th} of cooperative relays. Hence, the power of the j -th cooperative relay is given by

$$p_{r_j} = \min \left\{ p_{\max}, \frac{I_{\text{th}}}{L' \max_{i \in \{1, 2, \dots, L\}} \{(1-b_j) \cdot |g_{r_i, r_j}|^2\}} \right\} \quad (23)$$

where L' denotes the number of cooperative jammers.

Obviously, the optimization problem of (22) is a multi-constraint nonlinear programming problem, and the computational complexity exponentially increases with the number of relays, which is NP-hard to solve. However, traditional algorithms are difficult to get the good performance due to the slow convergence speed and poor convergence accuracy. To efficiently tackle the complicated problem, we propose a

quantum chemical reaction optimization (QCRO) algorithm to obtain the appropriate solution.

3 Methods

In this section, a novel intelligent algorithm named QCRO is proposed for multiple-relay selection in a secure massive MIMO two-way relay network. Inspired by the chemical reaction optimization (CRO) algorithm [39] and quantum evolutionary theory [9], QCRO employs a set of quantum molecules, which is varied by different quantum evolutionary rules. Here we introduce the principle of QCRO.

3.1 QCRO for optimization problem

In an L -dimensional space, (where L is the maximal dimension of the problem), there exist N quantum molecules. The n -th quantum molecule ($n=1,2,...,N$) of the t -th iteration is given by

$$\mathbf{x}_n^t = [x_{n,1}^t, x_{n,2}^t, \dots, x_{n,L}^t] \quad (24)$$

where $0 \leq x_{n,l}^t \leq 1$; $n=1,2,...,N$; $l=1,2,...,L$; $x_{n,l}^t$ denotes the l -th quantum bit of the n -th quantum molecule. For each quantum molecule, the quantum bits should be measured to the solution domain. The measurement state of the i -th quantum molecule can be obtained by the following rule:

$$\bar{x}_{n,l}^t = \begin{cases} 1, & \alpha_{n,l}^t > (x_{n,l}^t)^2 \\ 0, & \alpha_{n,l}^t \leq (x_{n,l}^t)^2 \end{cases} \quad (25)$$

where $\bar{x}_{n,l}^t$ denotes the l -th measurement state of the i -th quantum molecule, and $\alpha_{n,l}^t$ is a random number distributed in $[0,1]$.

The fitness value of the n -th quantum molecule is calculated by the fitness

function, which can be expressed as $f(\bar{\mathbf{x}}_n^t)$. For the maximum optimization problem, the global optimal solution $\bar{\rho}_{\text{best}}^t = [\bar{\rho}_{\text{best},1}^t, \bar{\rho}_{\text{best},2}^t, \dots, \bar{\rho}_{\text{best},L}^t]$ is denoted as the measurement state of the quantum molecule with the maximum fitness value until the t -th iteration.

In QCRO, the quantum molecules are updated by collision, decomposition, and synthesis. These processes are related to the kinetic energy (KE) of quantum molecules, where the top $\mu_1 N$ quantum molecules with the highest KE are updated by collision, $\mu_2 N$ quantum molecules with the smallest KE are updated by synthesis, and the remaining $\mu_3 N$ quantum molecules are updated by decomposition. μ_1 , μ_2 , and μ_3 are constants which respectively represent the reaction ratio of collision, synthesis, and decomposition. To make it easy, we sort the quantum molecules in a descending order according to the level of KE, and the n' -th quantum molecule is denoted by $\mathbf{x}_{n'}^t = [x_{n',1}^t, x_{n',2}^t, \dots, x_{n',L}^t]$ with the KE of $e_{n'}^t$. The generation of new quantum molecules is related to the quantum rotation angle and measurement states of previous quantum molecules. For collision, the n' -th quantum molecule is updated to a quantum molecule m , the quantum rotation angle and KE are given by

$$\theta_{m,l}^{t+1} = c_1 \cdot (\bar{x}_{g,l}^t - \bar{x}_{n',l}^t) \quad (26)$$

$$e_m^{t+1} = e_{n'}^t \cdot (1 - Ve) \quad (27)$$

where $m = n'$; $n' = 1, 2, \dots, \mu_1 N$; $l = 1, 2, \dots, L$; $\bar{x}_{g,l}^t$ denotes the l -th measurement state of the g -th quantum molecule with higher fitness value in the t -th iteration, $g \in \{1, 2, \dots, N\}$, $g \neq n'$. c_1 represents the weight coefficient, and Ve represents the loss rate of KE.

For decomposition, the n' -th quantum molecule is decomposed into quantum

289 molecule m and $m+1$, and the quantum rotation angles are respectively shown as

$$290 \quad \theta_{m,l}^{t+1} = \begin{cases} c_2 \cdot (\bar{\rho}_{\text{best},l}^t - \bar{x}_{n',l}^t) + c_3 \cdot (\bar{x}_{a,l}^t - \bar{x}_{n',l}^t), & \varphi_{m,l}^{t+1} < \kappa_1 \\ c_4 \cdot (\bar{x}_{g,l}^t - \bar{x}_{n',l}^t), & \text{else} \end{cases} \quad (28)$$

$$291 \quad \theta_{m+1,l}^{t+1} = \begin{cases} c_2 \cdot (\bar{\rho}_{\text{best},l}^t - \bar{x}_{n',l}^t) + c_3 \cdot (\bar{x}_{a,l}^t - \bar{x}_{n',l}^t), & \varphi_{m+1,l}^{t+1} < \kappa_1 \\ c_4 \cdot (\bar{x}_{g,l}^t - \bar{x}_{n',l}^t), & \text{else} \end{cases} \quad (29)$$

292 where $m = 2n' - \mu_1 N - 1$; $n' = \mu_1 N + 1, \mu_1 N + 2, \dots, \mu_1 N + \mu_3 N$; $l = 1, 2, \dots, L$; $g \in \{1, 2, \dots, N\}$,

293 $g \neq n'$; $\bar{x}_{a,l}^t$ denotes the l -th measurement state of a random quantum molecule in

294 the t -th iteration, $a \in \{1, 2, \dots, N\}$, $a \neq n'$; c_2 , c_3 and c_4 are weight coefficients.

295 κ_1 is the mutation probability which is a fixed parameter that determines the

296 decomposition style, $\varphi_{m,l}^{t+1}$ and $\varphi_{m+1,l}^{t+1}$ are random variables distributed from 0 to 1.

297 The KE of quantum molecule m and $m+1$ can be expressed by

$$298 \quad e_m^{t+1} = e_{n'}^t \cdot (1 - Ve) / 2 \quad (30)$$

$$299 \quad e_{m+1}^{t+1} = e_{n'}^t \cdot (1 - Ve) / 2 \quad (31)$$

300 For synthesis, the n' -th quantum molecule and the $(n'+1)$ -th quantum molecule

301 are synthesized into a new quantum molecule m , the quantum rotation angle and KE

302 are given by

$$303 \quad \theta_{m,l}^{t+1} = c_5 \cdot \omega_{m,l}^t \cdot (\bar{x}_{n'+1,l}^t - \bar{x}_{n',l}^t) \quad (32)$$

$$304 \quad e_m^{t+1} = (e_{n'}^t + e_{n'+1}^t) \cdot (1 - Ve) \quad (33)$$

305 where $m = (n' + \mu_1 N + 3\mu_3 N + 1) / 2$; $n' = \mu_1 N + \mu_3 N + 1, \mu_1 N + \mu_3 N + 3, \dots, N - 1$;

306 $l = 1, 2, \dots, L$; c_5 represents the weight coefficient; and $\omega_{m,l}^t$ is a random variable

307 distributed from 0 to 1.

The m -th and $(m+1)$ -th updated quantum molecules can be respectively obtained by

$$x_{m,l}^{t+1} = \begin{cases} \sqrt{1 - (x_{n',l}^t)^2}, & \theta_{m,l}^{t+1} = 0 \text{ and } \hat{\phi}_{m,l}^{t+1} \leq \kappa_2 \\ \text{abs}(x_{n',l}^t \cdot \cos \theta_{m,l}^{t+1} - \sqrt{1 - (x_{n',l}^t)^2} \cdot \sin \theta_{m,l}^{t+1}), & \text{else} \end{cases} \quad (34)$$

$$x_{m+1,l}^{t+1} = \begin{cases} \sqrt{1 - (x_{n',l}^t)^2}, & \theta_{m+1,l}^{t+1} = 0 \text{ and } \hat{\phi}_{m+1,l}^{t+1} \leq \kappa_2 \\ \text{abs}(x_{n',l}^t \cdot \cos \theta_{m+1,l}^{t+1} - \sqrt{1 - (x_{n',l}^t)^2} \cdot \sin \theta_{m+1,l}^{t+1}), & \text{else} \end{cases} \quad (35)$$

where $\hat{\phi}_{m,l}^{t+1}$ and $\hat{\phi}_{m+1,l}^{t+1}$ are random variables distributed from 0 to 1, κ_2 denotes the conversion probability, and $\text{abs}(\cdot)$ represents the absolute value function. For collision, $m = n'$; $n' = 1, 2, \dots, \mu_1 N$. For decomposition, $m = 2n' - \mu_1 N - 1$; $n' = \mu_1 N + 1, \mu_1 N + 2, \dots, \mu_1 N + \mu_3 N$. For synthesis, $m = (n' + \mu_1 N + 3\mu_3 N + 1) / 2$; $n' = \mu_1 N + \mu_3 N + 1, \mu_1 N + \mu_3 N + 3, \dots, N - 1$.

Then, we obtain the corresponding measurement states of the updated quantum molecules and calculate the fitness value. The measurement state of the quantum molecule with the maximum fitness value until the $(t+1)$ -th iteration is updated as the global optimal solution $\bar{\rho}_{\text{best}}^{t+1}$. The iteration ends when the QCRO algorithm achieves the terminal condition.

3.2 Process of multiple-relay selection based on QCRO

To tackle the MRS problem of (22) in secure massive MIMO two-way relay networks, for QCRO algorithm, the fitness function is set as

$$f(\bar{\mathbf{x}}_n^t) = \begin{cases} C_{\text{sum}}(\bar{\mathbf{x}}_n^t), & \text{satisfy constraint conditions} \\ 0, & \text{else} \end{cases} . \quad \text{For each quantum molecule, the}$$

measurement state is corresponding to the MRS result which should be optimized.

Hence, the optimal MRS result corresponds to the global optimal solution of QCRO

algorithm. In general, the process of MRS based on QCRO for secrecy sum-rate optimization can be shown in **Algorithm 1**.

Algorithm 1: Multiple-relay selection based on QCRO

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1 Input parameters of the secure massive MIMO two-way relay network;
2 Initialize the population of quantum molecules and other parameters of QCRO;
3 Set $t = 1$;
4 Obtain measurement states of all quantum molecules by (25);
5 Calculate the fitness value by the fitness function;
6 Obtain the global optimal solution $\bar{\rho}_{\text{best}}^t$;
7 repeat
    8 Sort the quantum molecules in a descending order according to the kinetic energy;
    9 Update the quantum molecules and by collision, decomposition, and synthesis;
    10 Obtain measurement states of the newly generated quantum molecules by (25);
    11 Calculate the fitness value of each updated quantum molecule;
    12 Update the global optimal solution until the $(t+1)$ -th iteration;
    13 Set $t = t + 1$;
14 until the QCRO algorithm achieves the terminal condition
15 Obtain the optimal MRS result according to the global optimal solution;
16 Output the optimal MRS result.

---

4 Results and discussion

Here we present the secrecy performance in secure massive MIMO two-way relay networks. We consider a two-dimensional network topology where L single-antenna relays are randomly located at $(50, 0)$ with the radius of 20, the BS and the legitimate user are located at the positions $(0, 0)$ and $(100, 0)$ (unit: meters), respectively. K single-antenna eavesdroppers are randomly located in the system. We set $M_t = 128$, $\xi = 3.8$, $L = 20$, and $I_{\text{th}} = -20\text{dBm}$. The system bandwidth $B = 100\text{MHz}$, and noise power spectral density $N_0 = -174\text{dBm/Hz}$. To reduce the implementation complexity, maximum ratio transmission (MRT) and maximum ratio combining (MRC) methods are adopted at the BS for precoding and receiving. The comparisons of the proposed

QCRO algorithm, existing intelligent algorithms and relay selection strategies are presented in the first part. For the second part, we illustrate the impact on the secrecy sum-rate of the cooperative transmission mode based on QCRO algorithm with various system parameters. All results are the average of 200 Monte-Carlo simulations.

4.1 Performance comparisons with QCRO

The comparisons of QCRO algorithm, particle swarm optimization (PSO) algorithm [40], chemical reaction optimization (CRO) algorithm [39], single-relay selection (SRS) strategy [32], and random multiple-relay selection (RMRS) strategy on the security performance are presented in Figs. 1 – 5. For comparison purpose, we set the maximum number of iterations for QCRO, PSO, and CRO algorithms to the same value, and all these algorithms are set to the same population size. The other parameters of PSO and CRO algorithms are set to the optimal values cited in [40] and [39], respectively. For QCRO algorithm, all quantum bits are initialized to 0.5 and the initial kinetic energy each quantum molecule is set to 1000. The parameter settings of QCRO algorithm are shown in **Table 2**.

Table 2 Parameter settings of QCRO algorithm

Parameter	Value
Population size (N)	60
Maximum iteration number	500
Loss rate of kinetic energy (Δe)	0.2
Reaction ratio of collision (μ_1)	0.55
Reaction ratio of synthesis (μ_2)	0.15
Reaction ratio of decomposition (μ_3)	0.3
Weight coefficient (c_1)	0.1
Weight coefficient (c_2)	0.1
Weight coefficient (c_3)	0.03
Weight coefficient (c_4)	0.03
Weight coefficient (c_5)	0.03
Mutation probability (κ_1)	0.5
Conversion probability (κ_2)	0.1/ L

The convergent performance of QCRO algorithm, PSO algorithm, CRO algorithm, SRS, and RMRS strategies are presented in **Fig. 1** with $p_{BS} = 35\text{dBm}$, $p_u = 30\text{dBm}$, $p_{\max} = 30\text{dBm}$, and $K=1$. We observe that QCRO algorithm has a fast convergence speed and a higher convergent accuracy throughout the iterations. For the MRS problem of (22), traditional CRO and PSO algorithms are prone to fall into local optimum in iteration processes. Since the proposed QCRO combines the merits of quantum calculation and preserves the diversity of chemical reaction process, QCRO has the strong optimization ability for solving complicated optimization problems. The results also illustrate that the prominent advantage of QCRO over the SRS and RMRS strategies on secrecy sum-rate in a massive MIMO system.

Fig. 1 Convergence performance comparisons

The security performance of QCRO, PSO, CRO, RMRS and SRS with the variation of p_{BS} , p_u , $p_{\max}$, and K are shown in Figs. 2 – 5. In **Fig. 2**, for most strategies, the secrecy sum-rate of the massive MIMO system increases along with p_{BS} . But the rising tendency begins to slow down when p_{BS} is over 15dBm. This phenomenon is caused by information leakage, which has a negative influence on the secrecy performance. According to (3) and (13), the eavesdropper may obtain more information from the BS with a higher p_{BS} , and the secrecy sum-rate may decrease

377 with p_{BS} when p_{BS} is over 25dBm.

378 **Fig. 2** Secrecy sum-rate in different p_{BS} with $p_u = 30\text{dBm}$, $p_{\max} = 30\text{dBm}$, and $K = 1$

380 **Fig. 3** Secrecy sum-rate in different p_u with $p_{BS} = 35\text{dBm}$, $p_{\max} = 30\text{dBm}$, and $K = 1$

382 **Fig. 4** Secrecy sum-rate in different $p_{\max}$ with $p_{BS} = 35\text{dBm}$, $p_u = 30\text{dBm}$, and $K = 1$

Figs. 3 – 4 illustrate the impact of different transmit power of the user and maximum transmit power of the cooperative relays on the security performance. For all strategies in **Fig. 3**, a higher secrecy sum-rate can be achieved by increasing p_u . The results in **Fig. 4** also illustrate that increasing $p_{\max}$ can boost the security performance. The reason is that a larger $p_{\max}$ will permit relays to broadcast the signals at a higher transmission power under certain interference conditions. After self-interference elimination, the increment of SINR at the legitimate devices is higher than that of the eavesdroppers.

Fig. 5 Secrecy sum-rate in different K with $p_{BS} = 35\text{dBm}$, $p_u = 30\text{dBm}$, and $p_{\max} = 30\text{dBm}$

The impact of different number of eavesdroppers on the secrecy sum-rate is presented in **Fig. 5**. The result shows that the existence of eavesdroppers has an adverse effect on the secrecy performance, and the information leakage increases along with K . That is because by increasing K , the probability of emerging an eavesdropper with a higher channel gain increases accordingly. For the non-colluding eavesdroppers, the information leakage is determined by the maximum received SINR at the eavesdroppers during the two transmission phases. From Figs. 2 – Fig. 5, we conclude that QCRO has great advantages over other strategies in improving the communication security of secure massive MIMO two-way relay networks.

4.2 Impact of different system parameters

The performance of the proposed cooperative transmission mode based on QCRO algorithm in different p_u and p_{BS} is studied in **Fig. 6**, where p_u increases from 0dBm to 40 dBm, p_{BS} =0dBm, 3dBm, 5dBm, and 10dBm, respectively. From the simulations, the system can obtain a higher secrecy sum-rate with a larger level of p_u at first. But when p_u is over 30dBm, the increment of secrecy sum-rate begins to slow down. For the cases of p_{BS} =3dBm, 5dBm, and 10dBm, the secrecy sum-rate decreases with p_u when p_u is over 35dBm. The reason is that the SINR received at the eavesdropper increases with p_u , which may cause more information leakage. Hence, we can appropriately increase p_{BS} to confuse the eavesdroppers.

Fig. 6 Secrecy sum-rate in different p_u and p_{BS} with $p_{\max} = 30$ dBm and $K = 1$

In **Fig. 7**, we investigate the impact of different $p_{\max}$ and p_u levels with $p_{\max}$ varying from 0dBm to 40 dBm, p_{BS} =0dBm, 5dBm, 10dBm, 20dBm, and 30dBm, respectively. From the simulations, the increasing trend of secrecy sum-rate with p_u is in accordance with the results of **Fig. 3**. We also observe that both higher levels of $p_{\max}$ and p_u can help boost the communication security. The reason is that a higher $p_{\max}$ can permit each relay to use more power for its own transmission. With the

increment of $p_{\max}$, the desired terminals can obtain higher transmission rates than that of the eavesdroppers according to the SIC criterion.

Fig. 7 Secrecy sum-rate in different $p_{\max}$ and p_u with $p_{BS} = 35$ dBm and $K = 1$

The influence of p_{BS} and number of eavesdroppers are studied in **Fig. 8**. In simulations, p_{BS} varying from -10 dBm to 20 dBm, and $K = 1, 3, 10, 20$, respectively. The results indicate that a larger number of eavesdroppers can cause more information leakage, which jeopardizes the communication security of massive MIMO system. For a certain value of K , we can obtain a higher secrecy sum-rate with a larger p_{BS} .

Fig. 8 Secrecy sum-rate in different p_{BS} and K with $p_u = 30$ dBm and $p_{\max} = 30$ dBm

The influence of different $p_{\max}$ and L in single and multiple eavesdropper cases are investigated in **Fig. 9**. We consider $K = 1$ and $K = 10$, $p_{\max}$ varies from -10 dBm

to 20dBm, and L increases from 5 to 20. The simulation results indicate that both higher $p_{\max}$ and more relays can boost the transmission security. Obviously, the secrecy sum-rate in the case of single eavesdropper is higher than that of multiple eavesdroppers.

Fig. 9 Secrecy sum-rate in different $p_{\max}$ and L with $p_{BS} = 35\text{dBm}$, $p_u = 30\text{dBm}$, and

$$K = \{1, 10\}$$

5 Conclusions

In this paper, we have designed a cooperative transmission mode to achieve the trade-off between the communication security and reliability in a massive MIMO system with two-way relay cooperation. Based on the multiple-relay collaboration strategy, some relays function as helper while other relays act as jammer to against the interception of eavesdroppers. Considering the system capacity, energy conservation, and QoS requirements, we have formulated the MRS problem in a secure massive MIMO two-way relay network. Then, we have introduced the implementation of multiple-relay collaboration strategy based on QCRO to optimize the secrecy sum-rate and simulation results have demonstrated its effectiveness in different communication scenarios. In future research, we will incorporate the efforts of this work with energy harvesting, network slicing, and ultra-dense heterogeneous

networks to meet the increasing demands of future wireless communication systems.

Abbreviations

IoE: Internet of Everything; MIMO: Multiple-input multiple-output; BS: Base station; QCRO: Quantum chemical reaction optimization; QoS: Quality of service; DT: Direct transmission; OWR: One-way relaying; TWR: Two-way relaying; MRS: Multiple-relay selection; CSI: Channel state information; TDD: Time-division duplexed; CRCJ: Cooperative relaying and cooperative jamming; AWGN: Additive white Gaussian noise; SINR: Signal-to-interference plus noise ratio; SIC: Self-interference cancellation; CRO: Chemical reaction optimization; KE: Kinetic energy; MRT: Maximum ratio transmission; MRC: Maximum ratio combining; PSO: Particle swarm optimization; SRS: Single-relay selection; RMRS: Random multiple-relay selection.

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Authors' contributions

Yumeng Su carried out experiments and theoretical analysis, and was a major contributor in writing the manuscript. Hongyuan Gao mainly provided the guidance for deriving these expressions. Shibo Zhang conceived of the study, and participated in its design and coordination. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analysed during this study are included in this article.

Competing interests

The authors declare that they have no competing interests.

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Figure title and legend

Fig. 1 Convergence performance comparisons.

Blue line: QCRO; yellow line: PSO; green line: CRO; pink line: RMRS; black line: SRS.

Fig. 2 Secrecy sum-rate in different p_{BS} with $p_u = 30\text{dBm}$, $p_{\max} = 30\text{dBm}$, and $K = 1$.

Blue line: QCRO; yellow line: PSO; green line: CRO; pink line: RMRS; black line: SRS.

Fig. 3 Secrecy sum-rate in different p_u with $p_{BS} = 35\text{dBm}$, $p_{\max} = 30\text{dBm}$, and $K = 1$.

Blue line: QCRO; yellow line: PSO; green line: CRO; pink line: RMRS; black line: SRS.

Fig. 4 Secrecy sum-rate in different $p_{\max}$ with $p_{BS} = 35\text{dBm}$, $p_u = 30\text{dBm}$, and $K = 1$.

Blue line: QCRO; yellow line: PSO; green line: CRO; pink line: RMRS; black line: SRS.

Fig. 5 Secrecy sum-rate in different K with $p_{BS} = 35\text{dBm}$, $p_u = 30\text{dBm}$, and $p_{\max} = 30\text{dBm}$

Blue line: QCRO; yellow line: PSO; green line: CRO; pink line: RMRS; black line: SRS.

Fig. 6 Secrecy sum-rate in different p_u and p_{BS} with $p_{\max} = 30\text{dBm}$ and $K = 1$.

Blue line: $p_{BS} = 10\text{dBm}$; green line: $p_{BS} = 5\text{dBm}$; yellow line: $p_{BS} = 3\text{dBm}$; pink line: $p_{BS} = 0\text{dBm}$.

Fig. 7 Secrecy sum-rate in different $p_{\max}$ and p_u with $p_{BS} = 35\text{dBm}$ and $K = 1$.

Blue line: $p_u = 30\text{dBm}$; green line: $p_u = 20\text{dBm}$; yellow line: $p_u = 10\text{dBm}$; pink line: $p_u = 5\text{dBm}$; black line: $p_u = 0\text{dBm}$.

593

594 **Fig. 8** Secrecy sum-rate in different p_{BS} and K with $p_u = 30\text{dBm}$ and $p_{\max} = 30\text{dBm}$.

595 Blue line: $K = 1$; green line: $K = 3$; yellow line: $K = 10$; pink line: $K = 20$.

596

597 **Fig. 9** Secrecy sum-rate in different $p_{\max}$ and L with $p_{BS} = 35\text{dBm}$, $p_u = 30\text{dBm}$, and
598 $K = \{1, 10\}$.

599 Blue line: $K = 1, L = 20$; green line: $K = 1, L = 10$; yellow line: $K = 1, L = 5$; pink line:

600 $K = 10, L = 20$; black line: $K = 10, L = 10$; purple line: $K = 10, L = 5$.

601

Figures

Figure 1

Convergence performance comparisons

Figure 2

Secrecy sum-rate in different PBS with $P_u = 30$ dBm, $P_{max} = 30$ dBm, and $K=1$

Figure 3

Secrecy sum-rate in different Pu with PBS =35dBm, Pmax = 35dBm, and K=1

Figure 4

Secrecy sum-rate in different Pmax with PBS =35dBm, Pu = 30dBm, and K=1

Figure 5

Secrecy sum-rate in different K with $P_{BS} = 35\text{dBm}$, $P_u = 30\text{dBm}$, and $P_{max} = 30\text{dBm}$

Figure 6

Secrecy sum-rate in different P_u with PBS with $P_{\max} = 30\text{dBm}$, and $K=1$

Figure 7

Secrecy sum-rate in different $P_{\max}$ and P_u with PBS = 35dBm, and $K=1$

Figure 8

Secrecy sum-rate in different PBS and K with $P_u = 30\text{dBm}$, and $p_{\max}=30\text{dBm}$

Figure 9

Secrecy sum-rate in different $P_{\max}$ and L with $P_B = 35\text{dBm}$, $p_u = 30\text{dBm}$ and $K=\{1,10\}$