Confidential Communications for Mobile UAV Relaying Network

Chenglan Ji, Zhenyu Na(✉), and Zilong Feng

School of Information Science and Technology, Dalian Maritime University,
Dalian, China
`nazhenyu@dlmu.edu.cn`

Abstract. In recent years, unmanned aerial vehicle (UAV) communication has not only attracted extensive discussion in academic circles, but also has been applied to practical scenarios. With the rapid development of UAV communication, its secrecy issues have gradually become prominent. In this paper, the physical layer security of mobile UAV relaying network is studied. We give a scheme of confidential communication to ensure the integrity and confidentiality of information. By optimizing the dynamic position of the UAV and transmit power, our goal is to maximize the minimum secrecy rate. Because the problem we put forward can not be solved directly by the solver, we divide the problem into two sub-problems to analyse. The simulation results show that our program improves the fairness of secrecy communication, and the physical layer security of the mobile UAV relaying network has been enhanced.

Keywords: UAV · Mobile relay · Secrecy · Convex optimization

1 Introduction

Unmanned aerial vehicle (UAV) has the characteristics of small size, low cost, convenient use, and so on. From the perspective of the global market, the industry demand and investment scale of UAV have grown steadily. In the future, UAV is likely to play a major role in express delivery industry, public safety, journalism, and other industries [1–4]. In recent years, the research and development of UAV at home and abroad has paid unprecedented attention, among which UAV communication is one of the key research. A detailed tutorial on the UAV communication networks are provided in [5]. Among them, the more comprehensive examples of UAV communication are introduced, such as aerial UAV base station, cellular-connected UAVs, flying ad hoc networks etc. On this basis, possible research directions and tools to solve such problems are given. With the deepening and comprehensive research of UAV communication, the secrecy of UAV communication has also received attention.

In [5], we can judge that the channel of the air-to-ground link is dominated by line-of-sight (LoS). Due to the broadcast nature of the wireless channel, while

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the UAV communication system provides high-quality communication services to the destination, the possibility of eavesdroppers obtaining information is greatly increased. However, the complexity of traditional encryption and decryption algorithms is too high. Taking advantage of the randomness of the channel itself, physical layer security technology has become a key technology for UAV confidential communication, where some meaningful researches on this perspective can be found in, e.g., [6–10]. Among them, the survey articles [6–8] give several schemes for secure transmission of aerial UAV base station. Prior work [9] adopts the idea of multi-UAV relaying communication network to reduce the probability of eavesdropping and gives the expression under Rician fading channel. Gao et al. [10] maximizes the secrecy achievable rate of target user under the UAV relaying network.

To sum up, researchers have done a lot of work on how UAV acts as aerial base station to deal with malicious eavesdropping. Secure communication of mobile UAV relaying system is equally important. In [9,10], a secure relaying network for cooperative communication of multiple UAVs is given. However, in the above UAV relaying system, the UAV only communicates confidentially with one destination. Based on this, we propose mobile UAV relaying network in a multi-user scenario. Since the problem is not easy to solve directly, we separate it into two sub-problems and give the corresponding low-complexity algorithms. Finally, we give the simulation results to verify the effectiveness of the program.

2 System Model and Problem Formulation

2.1 System Model

This paper studies a mobile UAV relaying network, which is composed of a ground base station (S), a UAV relay (R), an eavesdropper (E), and a group of target users (D). Assuming that the base station, the eavesdropper, and the target users are located on a plane, which is denoted as the *xoy* plane. The coordinate system is established with the base station as the origin, then the eavesdropper's coordinate is $\mathbf{W}_{\mathrm{e}} = [x_{\mathrm{e}}, y_{\mathrm{e}}]^{\mathrm{T}}$, and coordinate of the target user $k \in \mathcal{K} = \{1, ..., K\}$ is $\mathbf{W}_k = [x_k, y_k]^{\mathrm{T}}$. During the mission time T, the vertical coordinate of the dynamic UAV is fixed as H, and its horizontal coordinate is marked as $\mathbf{q}[t] = [x[t], y[t]]^{\mathrm{T}}, t \in T$. In order to solve the problem easily, we cut the task time T into N time slots, then the coordinate of UAV in the nth time slot is expressed as $[\mathbf{q}[n], H]^{\mathrm{T}}$, where $\mathbf{q}[n] = [x[n], y[n]]^{\mathrm{T}}, n \in \mathcal{N} = \{1, ..., N\}$. The position of the UAV in any time slot is limited by the maximum flight speed $V_{\max}$. The relationship between them is as follows

$$\|\mathbf{q}[n+1] - \mathbf{q}[n]\|^2 \leq (V_{\max}\frac{T}{N})^2, n = 1, ..., N-1 \tag{1}$$

The trajectory of UAV in single route mode is constrained by the following

$$\mathbf{q}[1] = \mathbf{q}_{\mathrm{ini}} \tag{2a}$$

$$\mathbf{q}[N] = \mathbf{q}_{\mathrm{end}} \tag{2b}$$

Among them, $\mathbf{q}_{\mathrm{ini}}, \mathbf{q}_{\mathrm{end}}$ refer to the start point and end point of the UAV's trajectory.

On the basis of the LoS channel model, we can obtain the channel gains of link S-R, R-E, R-D, which are shown as follows

$$h_{\mathrm{r}}\left[n\right] = \frac{\beta_0}{H^2 + \left\|\mathbf{q}\left[n\right]\right\|^2}, \forall n \tag{3a}$$

$$h_{\mathrm{e}}\left[n\right] = \frac{\beta_0}{H^2 + \left\|\mathbf{q}\left[n\right] - \mathbf{W}_{\mathrm{e}}\right\|^2}, \forall n \tag{3b}$$

$$h_k\left[n\right] = \frac{\beta_0}{H^2 + \left\|\mathbf{q}\left[n\right] - \mathbf{W}_k\right\|^2}, \forall n, k \tag{3c}$$

where β_0 refers to the channel power gain at the reference distance $d_0 = 1\mathrm{m}$. The communication between the UAV and the target users adopts time division multiple access technology, which means that the UAV only secretly transmits information with a receiving terminal at any time slot. We introduce a significative symbol $\alpha_k\left[n\right]$ to record scheduling information, then $\alpha_k\left[n\right]$ should meet the following conditions

$$\alpha_k\left[n\right] \in \left\{0, 1\right\}, \forall k, n \tag{4a}$$

$$\sum_{k=1}^{K} \alpha_k\left[n\right] \leq 1, \forall n \tag{4b}$$

The transmit power of base station and UAV is given by $p_{\mathrm{s}}\left[n\right], p_{\mathrm{r}}\left[n\right], \forall n$ respectively. Its constraints may be expressed as

$$\sum_{n=1}^{N} p_{\mathrm{s}}\left[n\right] \leq N P_{\mathrm{s}}^{\mathrm{ave}} \tag{5a}$$

$$\sum_{n=1}^{N} p_{\mathrm{r}}\left[n\right] \leq N P_{\mathrm{r}}^{\mathrm{ave}} \tag{5b}$$

$$p_{\mathrm{s}}\left[n\right] \geq 0, \forall n \tag{5c}$$

$$p_{\mathrm{r}}\left[n\right] \geq 0, \forall n \tag{5d}$$

where, $P_{\mathrm{s}}^{\mathrm{ave}}, P_{\mathrm{r}}^{\mathrm{ave}}$ indicate average power of base station and UAV respectively. We introduce a new variable $\rho_0 = \frac{\beta_0}{\xi}$, where ξ represents the power of the noise. Then, the maximum achievable rate of the link S-R, R-D, R-E are respectively presented as

$$R_{\mathrm{r}}[n] = \log_2\left(1 + \frac{p_{\mathrm{s}}[n]\,\rho_0}{H^2 + x[n]^2 + y[n]^2}\right), \forall n \tag{6a}$$

$$R_k[n] = \log_2\left(1 + \frac{p_{\mathrm{r}}[n]\,\rho_0}{H^2 + (x[n] - x_k)^2 + (y[n] - y_k)^2}\right), \forall n, k \tag{6b}$$

$$R_{\mathrm{e}}[n] = \log_2\left(1 + \frac{p_{\mathrm{r}}[n]\,\rho_0}{H^2 + (x[n] - x_{\mathrm{e}})^2 + (y[n] - y_{\mathrm{e}})^2}\right), \forall n \tag{6c}$$

Therefore, our goal is specifically described as

$$R_{sk} = \frac{1}{N}\sum_{n=1}^{N} \alpha_k[n]\left[R_k[n] - R_{\mathrm{e}}[n]\right], \forall k \tag{7}$$

Because the UAV acts as a relay for confidential communication, we consider the following information causality constraints

$$\sum_{n=1}^{m} \alpha_k[n]\,R_k[n] \le \sum_{n=1}^{m} R_{\mathrm{r}}[n], \forall m, k \tag{8a}$$

$$\sum_{n=1}^{m} R_{\mathrm{e}}[n] \le \sum_{n=1}^{m} R_{\mathrm{r}}[n], \forall m \tag{8b}$$

2.2 Problem Formulation

Based on the above analysis, the single route optimization problem is formulated as follows

$$\max_{\alpha_k[n], p_{\mathrm{s}}[n], p_{\mathrm{r}}[n], x[n], y[n]} \varphi \tag{9a}$$

$$\text{s.t.} \quad R_{sk} \ge \varphi \tag{9b}$$

$$(1), (2), (4), (5), (8). \tag{9c}$$

It can be observed that both the objective function and the causality constraints are non-convex. $\alpha_k[n]$ is an integer variable and involves multiple constraints. Therefore, this problem we proposed can not be solved directly with convex optimization tools.

3 Problem Formulation

Due to the complexity of the problem and the coupling of variables, we simplify it into two sub-problems: UAV-user association $\mathbf{A} = \{\alpha_k[n], \forall k, n\}$ optimization and transmit power and UAV trajectory $\mathbf{B} = \{p_{\mathrm{s}}[n], p_{\mathrm{r}}[n], x[n], y[n], \forall n\}$ optimization.

3.1 UAV-User Association Optimization

Since $\alpha_k[n]$ is an integer variable that is not easy to handle, we relax it into a continuous variable, so we can use $0 \le \alpha_k[n] \le 1, \forall k, n$ to replace the constraint (4a). Given the power and trajectory, the optimization problem of UAV-user association is expressed as follows

$$\max_{\alpha_k[n]} \quad \varphi \tag{10a}$$

$$\text{s.t.} \quad \frac{1}{N}\sum_{n=1}^{N}\alpha_k[n]\left[R_k[n] - R_{\mathrm{e}}[n]\right] \ge \varphi, \forall k \tag{10b}$$

$$\sum_{n=1}^{m}\alpha_k[n]\,R_k[n] \le \sum_{n=1}^{m}R_{\mathrm{r}}[n], \forall m, k \tag{10c}$$

$$0 \le \alpha_k[n] \le 1, \forall k, n \tag{10d}$$

$$\sum_{k=1}^{K}\alpha_k[n] \le 1, \forall n \tag{10e}$$

This problem contains linear objective function and constraints that can be easily solved using convex optimization tools.

3.2 Transmit Power and UAV Trajectory

Firstly, introduce two inequalities, whose process has been demonstrated in [11].

$$\ln(1+\frac{1}{xy}) \ge \ln(1+\frac{1}{x^r y^r}) + \frac{x^r y^r}{x^r y^r + 1}(2 - \frac{x}{x^r} - \frac{y}{y^r}) \tag{11}$$

$$\ln(1+\frac{x}{y}) \le \ln(1+\frac{x^r}{y^r}) + (\frac{1}{1+\frac{x^r}{y^r}})[\frac{1}{2y}(\frac{x^2}{x^r} + x^r) - \frac{x^r}{y^r}] \tag{12}$$

where $x > 0, y > 0, r > 0$.

Lemma 1. *The non-convex constraint* (9b) *is transformed into a convex constraint, as shown below*

$$\frac{1}{N}\sum_{n=1}^{N}\alpha_k[n]\left[R_k^{\mathrm{lb}}[n] - R_e^{\mathrm{up}}[n]\right] \ge \varphi, \forall k \tag{13}$$

where,

$$R_k^{\mathrm{lb}}[n] = \log_2(\mathrm{e})\ln(1+\frac{p_{\mathrm{r}}^l[n]\rho_0}{d_k^l[n]}) + \frac{\log_2(\mathrm{e})p_{\mathrm{r}}^l[n]\rho_0}{d_k^l[n] + p_{\mathrm{r}}^l[n]\rho_0}(2 - \frac{p_{\mathrm{r}}^l[n]}{p_{\mathrm{r}}[n]} - \frac{d_k[n]}{d_k^l[n]}) \tag{14}$$

$$\begin{aligned} R_{\mathrm{e}}^{\mathrm{up}}[n] = {} & \log_2(\mathrm{e})\ln(1+\frac{p_{\mathrm{r}}^l[n]\rho_0}{d_{\mathrm{e}}^l[n]}) \\ & + \frac{\log_2(\mathrm{e})d_{\mathrm{e}}^l[n]}{d_{\mathrm{e}}^l[n] + p_{\mathrm{r}}^l[n]\rho_0}(\frac{1}{2d_{\mathrm{e}}[n]}(\frac{{p_{\mathrm{r}}}^2[n]\rho_0}{p_{\mathrm{r}}^l[n]} + p_{\mathrm{r}}^l[n]\rho_0) - \frac{p_{\mathrm{r}}^l[n]\rho_0}{d_{\mathrm{e}}^l[n]}) \end{aligned} \tag{15}$$

where,

$$d_k[n] \geq (x_k - x[n])^2 + (y_k - y[n])^2 + H^2 \tag{16}$$

$$\begin{aligned} d_{\mathrm{e}}[n] \leq &(x^l[n] - x_{\mathrm{e}})^2 + (y^l[n] - y_{\mathrm{e}})^2 + H^2 \\ &+ 2(x^l[n] - x_{\mathrm{e}})(x[n] - x^l[n]) + 2(y^l[n] - y_{\mathrm{e}})(y[n] - y^l[n]) \end{aligned} \tag{17}$$

Proof. Firstly, define a slack variable $d_k[n]$ to satisfy inequality (16), then $R_k[n] \geq \log_2(1 + \frac{p_{\mathrm{r}}[n]\rho_0}{d_k[n]})$. According to inequality (11), we can get $R_k^{\mathrm{lb}}[n]$, which is the lower bound of $R_k[n]$. Finally, establish the following inequality

$$d_{\mathrm{e}}[n] \leq (x_{\mathrm{e}} - x[n])^2 + (y_{\mathrm{e}} - y[n])^2 + H^2 \tag{18}$$

which is a non-convex constraint of the UAV horizontal coordinate. The right side of the formula can be transformed into a convex constraint (17) by Taylor expansion.

According to the inequality (12) given above, the upper bound of the $R_{\mathrm{e}}[n]$ is obtained, that is

$$R_{\mathrm{e}}[n] \leq \log_2(1 + \frac{p_{\mathrm{r}}[n]\rho_0}{d_{\mathrm{e}}[n]}) \leq R_{\mathrm{e}}^{\mathrm{up}}[n]. \tag{19}$$

It can be seen that formulas (13)–(17) are convex constraints on optimization variables. Therefore, we can use them to approximate the non-convex constraint (9b).

Lemma 2. *Non-convex constraint (8a) can be transformed into convex constraint through successive convex approximation, namely*

$$\sum_{n=1}^{m} \alpha_k[n]\, R_k^{\mathrm{up}}[n] \leq \sum_{n=1}^{m} R_{\mathrm{r}}^{\mathrm{lb}}[n], \forall m, k \tag{20}$$

where,

$$\begin{aligned} R_k^{\mathrm{up}}[n] = &\log_2(\mathrm{e})\ln(1 + \frac{p_{\mathrm{r}}^l[n]\rho_0}{d_{k1}^l[n]}) \\ &+ \frac{\log_2(\mathrm{e}) d_{k1}^l[n]}{d_{k1}^l[n] + p_{\mathrm{r}}^l[n]\rho_0}(\frac{1}{2d_{k1}[n]}(\frac{{p_{\mathrm{r}}}^2[n]\rho_0}{p_{\mathrm{r}}^l[n]} + p_{\mathrm{r}}^l[n]\rho_0) - \frac{p_{\mathrm{r}}^l[n]\rho_0}{d_{k1}^l[n]}) \end{aligned} \tag{21}$$

$$R_{\mathrm{r}}^{\mathrm{lb}}[n] = \log_2(\mathrm{e})\ln(1 + \frac{p_{\mathrm{s}}^l[n]\rho_0}{d_{\mathrm{s}}^l[n]}) + \frac{\log_2(\mathrm{e}) p_{\mathrm{s}}^l[n]\rho_0}{d_{\mathrm{s}}^l[n] + p_{\mathrm{s}}^l[n]\rho_0}(2 - \frac{p_{\mathrm{s}}^l[n]}{p_{\mathrm{s}}[n]} - \frac{d_{\mathrm{s}}[n]}{d_{\mathrm{s}}^l[n]}) \tag{22}$$

where,

$$\begin{aligned} d_{k1}[n] \leq &(x^l[n] - x_k)^2 + (y^l[n] - y_k)^2 + H^2 \\ &+ 2(x^l[n] - x_k)(x[n] - x^l[n]) + 2(y^l[n] - y_k)(y[n] - y^l[n]) \end{aligned} \tag{23}$$

$$d_{\mathrm{s}}[n] \geq (x[n])^2 + (y[n])^2 + H^2 \tag{24}$$

The non-convex constraint (8b) can be replaced with the following convex constraint

$$\sum_{n=1}^{m} R_{\mathrm{e}}^{\mathrm{up}}\left[n\right] \leq \sum_{n=1}^{m} R_{\mathrm{r}}^{\mathrm{lb}}\left[n\right], \forall m \tag{25}$$

Proof. First, define an intermediate variable $d_{k1}[n]$ to satisfy the following inequality

$$d_{k1}[n] \leq (x_k - x[n])^2 + (y_k - y[n])^2 + H^2 \tag{26}$$

Then obtain the following continuous inequalities according to inequality (12)

$$R_k[n] \leq \log_2(1 + \frac{p_{\mathrm{r}}[n]\rho_0}{d_{k1}[n]}) \leq R_k^{\mathrm{up}}[n] \tag{27}$$

In addition, define a slack variable $d_{\mathrm{s}}[n]$ to satisfy inequality (24), then $R_{\mathrm{r}}[n] \geq \log_2(1 + \frac{p_{\mathrm{s}}[n]\rho_0}{d_{\mathrm{s}}[n]})$. According to inequality (11), we can get $R_{\mathrm{r}}^{\mathrm{lb}}[n]$, which is the lower bound of $R_{\mathrm{r}}[n]$.

Formula (26) is non-convex, and the right part of it can be transformed into convex constraint (23) by Taylor expansion. Therefore, the non-convex constraint (8a) can be approximately replaced by (20)–(24). The derivation process of $R_{\mathrm{e}}^{\mathrm{up}}[n]$ in formula (25) has been proved in **Lemma** 1, and the derivation process of $R_{\mathrm{r}}^{\mathrm{lb}}[n]$ has also been proved. Therefore, the convex constraint (25) can approximately replace the non-convex constraint (8b).

Theorem 1. *Based on the* $p_{\mathrm{s}}^l[n], p_{\mathrm{r}}^l[n], x^l[n], y^l[n], d_k^l[n]$, *and* $d_{k1}^l[n]$ *obtained in the* r*th iteration, at the* $r+1$*th iteration, the power and trajectory optimization problem is described as follows*

$$\max_{p_{\mathrm{s}}[n],p_{\mathrm{r}}[n],x[n],y[n],d_k[n],d_{\mathrm{e}}[n],d_{k1}[n],d_{\mathrm{s}}[n]} \varphi \tag{28a}$$

$$\text{s.t.} \quad (13)-(17),(20)-(25). \tag{28b}$$

4 Numerical Results

In this section, simulation results are presented to verify the UAV relaying scheme that improves physical layer security. First, we studied whether the UAV trajectory can be dynamically adjusted when the eavesdropper's position changes. Secondly, we investigated the average confidentiality rate of each target user before and after the variable optimization.

For the mobile UAV relaying network we proposed, the three-dimensional coordinate of the base station is fixed to $(0,0,0)^{\mathrm{T}}$. UAV transmits information at a fixed height $H = 100$m. The eavesdropper is randomly distributed on the horizontal plane, and the target users are also randomly distributed on the horizontal plane, but there is a certain distance from the ground base station. Simulation parameters are set as follows: $K = 5, \beta_0 = -60$ dB$, \sigma^2 = -110$ dB$, V_{\max} = 50$ m/s$, T = 60$ s$, N = 60, P_{\mathrm{s}}^{\mathrm{ave}} = 1$ W$, P_{\mathrm{r}}^{\mathrm{ave}} = 1$ W.

Figures 1 and 2 show the adaptive adjustment of the UAV's trajectory when the eavesdropper's position changes. For the location of the eavesdropper, we selected two representative cases, namely near to the base station and far away from the base station. It can be seen that in the two cases, the UAV can be far away from the eavesdropper and close to the each target user to transmit information. This shows that our algorithm is effective for any eavesdropping position. Figure 3 shows the transmit power of the UAV and base station during the mission time.

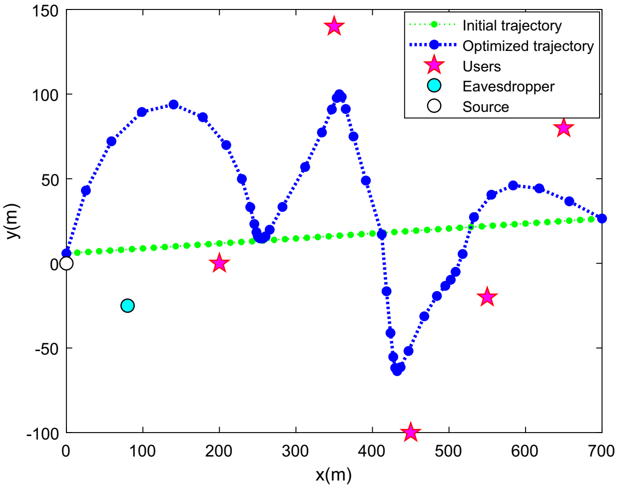

Fig. 1. UAV trajectory in the first position of the eavesdropper.

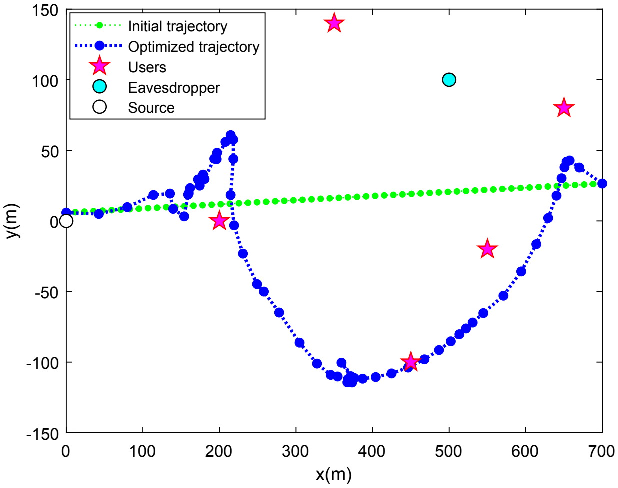

Fig. 2. UAV trajectory in the second position of the eavesdropper.

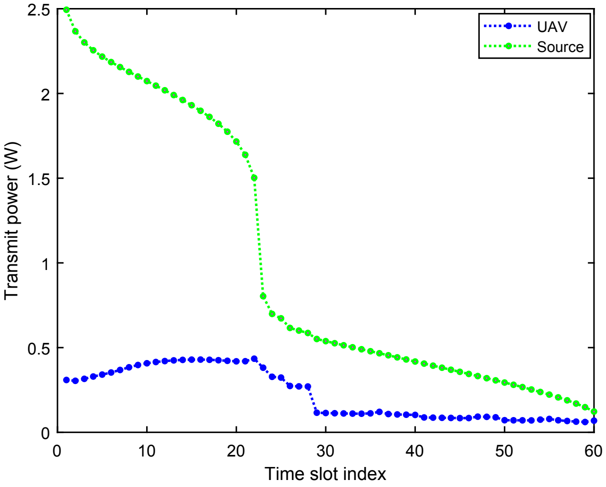

Fig. 3. Transmit power of the UAV and base station.

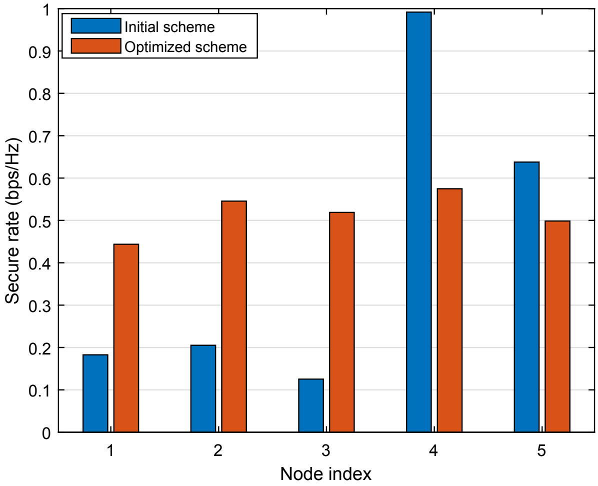

Fig. 4. Comparison chart of average security rate of each user.

Figure 4 shows the average secrecy rate of five users before and after algorithm optimization. It can be seen from the figure that there is a serious unfair phenomenon in confidential communication between users before optimization. The communication of user 4 and user 5 is rarely eavesdropped. However, user 1, user 2, and user 3 have serious eavesdropping phenomenon. After optimization, there is no great difference between the secrecy rate of the five users, which eliminates the unfairness of communication security among users.

5 Conclusion

This paper investigates the problem of confidential communication in mobile UAV relaying network from the perspective of physical layer security. Using time division multiple access technology, UAV can only communicate with one target user secretly in one time slot. By optimizing the three coupling variables of user scheduling, transmit power, and UAV trajectory, the minimum average secrecy rate among all users is maximized. The problem has been proved to be a non-convex optimization. The original problem is simplified into two sub-problems, and the best results are obtained through standard convex optimization tools. The simulation results prove that the algorithm improves the secrecy of mobile UAV relaying network.

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