Secure transmission strategy of multi UAV relays in jamming environment

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Abstract: This paper studies a multi UAV relays communication system based on secure transmission strategy in jamming environment. In the multi UAV relays communication system with interference, we use the physical layer security technology based on the physical layer to maximize the minimum average rate by optimizing the flight trajectory and resource allocation of the signal source and UAV relays, and adjust the channel state information of the legal communication channel, so as to improve the communication performance of the legal channel. Since the optimization problem and constraints are nonconvex and cannot be solved directly, we decompose it into two sub optimization problems: interference optimization and strategy optimization, which are solved respectively. Finally, the joint optimal solution of the original optimization problem is obtained by alternating iterative optimization, the simulation results show that by jointly optimizing the transmission power and flight trajectory of signal source and UAV relays, the influence of interference source on wireless communication is reduced and safer communication is realized.

1. Introduction
With the commercialization of 5G, UAV plays an irreplaceable role in wireless communication application scenarios. Unmanned aerial vehicle (UAV) is widely used in the field of wireless communication, especially in military communication, where wireless communication is often used as the main means of communication because of its flexibility and mobility, which can meet the communication requirements of a large coverage range [2]. Wireless communication is mainly realized by wireless transmitter and receiver, which can solve the problem that the communication line needs to be set up in advance in wired communication. However, wireless communication has limited communication distance and is prone to interference from other signals on the ground, so its reliability is poor [5]. Taking UAV as the carrier of communication transmitter and receiver can effectively increase the communication distance of wireless communication, and improve the reliability and anti-interference
capability of transmission [4]. However, the wireless channel between UAV and ground equipment is open. In today's increasingly complex communication environment, communication security has gradually become the main issue to be considered in wireless communication network. There may be unknown disruptors in wireless communication networks, so physical Layer security (PLS) technology based on physical layer has received more and more attention. It can take advantage of the controllable maneuverability of UAVs, The communication performance of the legitimate channel can be improved by adjusting its flight trajectory and resource allocation [6].

Through the research on physical layer security technology at home and abroad, we can see that physical layer security design scheme has been widely used in the UAV communication system. In most studies, the channel between UAV and ground is considered as line-of-sight channel [3], and the safety performance of the system can be effectively improved by constructing related optimization problems and using physical layer design method to carry out reasonable planning [15]. The implementation of physical layer security utilizes the inherent randomness of noise and communication channels to limit the amount of information extracted by unauthorized receivers at the "bit" level. Physical layer security technology has many advantages. It can make use of the physical characteristics of wireless channels to process transmitted information by designing appropriate coding and signal processing methods, so as to improve the confidentiality of transmitted information and enable legitimate receivers to receive and decode safely [14].

However, previous studies did not fully consider the long distance between two communication points, and a single UAV relay could not well take into account the task of transmitting information and avoiding interference [11]. Therefore, in order to meet the requirements of secure communication in the military, we put forward a design scheme based on physical layer security technology to improve the security performance of long-distance communication network by planning deployment and resource allocation of multiple UAV relays in the communication network [10]. The design scheme proposed in this paper can provide a fast and effective solution for long-distance wireless secure communication. Meanwhile, the design idea based on physical layer security technology can also be popularized and applied to a more complex communication environment, providing guidance for the rapid realization of secure communication in different scenarios.

2. Material and Methods

2.1 Interference Optimization Problem

In this paper, we consider the long-distance wireless communication between signal source and target point, and they transmit information through multi-hop UAV relay [1]. Because of the accumulation of wireless channels, the receiver is easily affected by other interference signals. Therefore, we assume that there are interference sources with uncertain location information between them, which will send interference signals to interfere with the communication between the target point and the relay UAV, thus affecting the information transmission.

Firstly, the communication system model is constructed. It is assumed that the signal source and the target point are far away from each other and cannot communicate with each other directly. Therefore, the multi-hop UAV relay network is used to transmit information between them by virtue of the characteristics of flexible deployment and fast movement of UAV [12]. In the communication process between the signal source and the target point, the signal source first sends the information to the first UAV relay, and after a delay time, it sends the information to the second UAV relay, and so on, until the last UAV relay sends the information to the target point. At the same time, m interference sources with uncertain location information exist on the ground. Assuming that the interference sources are located within the circle with the center of the circle \((X_m, Y_m)\) and the radius \(Q_m\) of the circle, we cannot determine their exact position. Therefore, there is a certain error between the actual position and the estimated center of the circle, namely

\[
x_m = x_{em} + \Delta x_m, \quad y_m = y_{em} + \Delta y_m
\]
As \((x_m, y_m)\) indicates the actual location of the interference source, \((x_{s}, y_{s})\) represents the estimated location of the interference source. The estimation error is satisfied

\[ \Delta x_m^2 + \Delta y_m^2 \leq Q_m^2 \] (2)

The communication system model is shown in Figure 1. Under this model, a Cartesian coordinate system is established, and the coordinates of signal source and target point are respectively set as \(q_s = [x_s, y_s]^T\) and \(q_D = [x_D, y_D]^T\). The interference source seat is marked as \(q_m = [x_m, y_m]^T\). Assume that the flight height of all UAV relays is fixed height \(H\), where \(H\) meets the minimum safe flight height of UAV to avoid collision, and mark the sitting of the kth UAV at time \(t\) as \(w_k = [x_k(t)^T, H]^T\). All of the above coordinates can be obtained by GPS.

For the convenience of analysis, we divide the flight time \(T\) of UAV to perform tasks into \(N\) time gaps, where each time gap has the same length, \(T = N \Delta t\). It is assumed that each time gap is small enough that the position of the UAV within each time gap can be considered fixed. Therefore, the coordinates of the UAV can also be expressed as \(w_k = [x_k(t)^T, H]^T\), among \(w_k = [x_k(t)^T, y_k(t)]^T\). So the trajectory of the drone over a given period of time can be represented by a series of points. The maximum flight distance of UAV in a time slot is limited by its speed, and the UAV must meet the minimum safe distance to prevent collision during flight, and the transmission power of UAV must meet certain conditions.

Figure 1 Multi-hop trunk communication model with interference sources

As UAV can communicate with ground node in the air, the channel between UAV relay and ground node is LoS channel (line-of-sight transmission channel) under the condition that there is no obstacle between the open air environment \([11]\). According to the channel characteristics, the channel gain of signal source and the 1st UAV relay, the Kth UAV relay and the target point, the Kth UAV relay and the K +1 UAV relay, and the Mth interference source and the Kth UAV relay in each time slot can be calculated respectively. Since both the interference source and the target point are on the ground, there is a large attenuation between them, so the channel between them is Rayleigh fading channel, and the path loss index is \(2 \leq k \leq 4\).

After the channel gain of each channel is obtained, the channel capacity of each time slot can be further obtained according to Shannon formula \([7]\). Considering that UAV relay adopts DF strategy in the relay transmission process, there is a delay of 1 time gap in the transmission process. At the same time, different channels occupy different frequency bands for transmission, and the distance between each frequency band is large enough, so the interference between channels can be ignored. In a relay transmission network, the information sent by the latter relay is entirely from the information sent by the previous relay within one time interval, which is also known as information causal constraint \([8]\). And since there are K time gaps between the signal source and the target, the signal source does not need to send a message after N-K+1 time interval. For the Kth UAV relay, in addition to the above, it does not send anything forward because it does not receive a message until the Kth time slot.
It can be analyzed from the above model that the receiving rate of the target point completely depends on the receiving rate relayed from the Kth UAV to the target point [9]. We consider the average receiving rate of the target point in the whole UAV relay flight process as the optimization target, then the average receiving rate of the target point can be expressed as:

$$\hat{R}_{K,D} = \frac{1}{N} \sum_{n=1}^{N} R_{K,D}[n] = \frac{1}{N} \sum_{n=1}^{N} \left( \log_2 \left( 1 + \frac{P_k[n]g_{K,D}[n]}{\sum_{m=0}^{N} P_m g_{m,D} + \sigma^2} \right) \right)$$  \hspace{1cm} (3)$$

Since the location information of the interference source is uncertain, we can only maximize the average reception rate of the Kth UAV relayed to the target point in the worst case. Then, we analyzed the constraints that UAV relay and signal source need to meet in the system model. Meanwhile, we took UAV relay track and transmission power of signal source and UAV relay as optimization variables of the optimization problem, so the optimization problem can be described as follows:

$$\max_{w_{v_k,w_{v_k}}} \min_{k} \frac{1}{N} \sum_{n=1}^{N} R_{K,D}[n], \forall k$$  \hspace{1cm} (4)$$

s.t. \quad ||w_k[1] - w_{0,k}|| \leq d_{\max}, \forall k$$  \hspace{1cm} (5)$$

$$||w_{v_k} - w_k[N]|| \leq d_{\max}, \forall k$$  \hspace{1cm} (6)$$

$$\frac{1}{N} \sum_{n=1}^{N} P_n[n] \leq \bar{P}_s, \forall n$$  \hspace{1cm} (7)$$

$$\frac{1}{N} \sum_{n=1}^{N} P_k[n] \leq \bar{P}_k, \forall n$$  \hspace{1cm} (8)$$

Among $d_{\max}$ Represents the maximum distance that the UAV can fly in a time slot, $w_{0,k}$, $w_{v_k}$ Represents the initial position and terminal position of the Kth UAV, $d_{\min}$ Represents the minimum safe distance between any two UAVs. $\bar{P}_s$, $\bar{P}_k$, $\bar{P}_{s,max}$ Denotes the transmitted average power and peak power of the signal source, $\bar{P}_k$, $P_{k,\text{max}}$ Represents the transmitting average power and peak power of the Kth UAV relay.

2.2 Optimization Strategy

Because the optimization problem contains random variables $\xi$, To simplify the optimization problem, we use the approximate result of this expression. Because it's for random variables $\xi$ Is a convex function, Therefore, jenson's inequality [9] can be used to obtain the lower bound of the channel capacity of the Kth UAV and the target point, namely:

$$\hat{R}_{\xi,D}[n] = \log \left( 1 + \frac{P_s[n]g_{\xi,D}[n]}{\sum_{n=0}^{N} P_n[n]g_{\xi,n} + \sigma^2} \right) \geq \log \left( 1 + \frac{P_s[n]g_{\xi,D}[n]}{\sum_{n=0}^{N} P_n[n]g_{\xi,n} + \sigma^2} \right)$$  \hspace{1cm} (9)$$

In the next step, we will solve this optimization problem. Since the optimization variables include the trajectory of UAV relay and the transmitting power of the signal source and UAV relay, the optimization problem is non-convex for the joint optimization variable, so the joint optimization variable cannot be solved directly. Therefore, we decomposed the optimization problem into two sub-optimization problems [1] to optimize the trajectory variable and the transmitting power variable respectively, and then solved them alternately iteratively until the optimization algorithm converges. Finally, the joint optimal solution satisfying the conditions can be obtained.
2.2.1 Optimization of transmitting power

The above optimization problem is transformed into a sub-problem of optimizing only the transmitting power of signal source and UAV relay, in which the flight trajectory of UAV relay is fixed [3]. Therefore, the constraint condition is only about transmitted power, and the sub-optimization problem can be expressed as:

\[
\max_{P_k} \sum_{n=1}^{N} \log_2 \left( 1 + P_k[n] \alpha_{K,D}[n] \right), \forall k
\]

(10)

\[
\alpha_{K,D}[n] = \frac{H^2 + \|q_D - w_k[n]\|^2}{\sum p_m \|q_D - q_m\|^2 + \sigma^2} = \frac{\gamma_0}{\sum p_m \|q_D - q_m\|^2 + 1}
\]

(11)

Among \(\gamma_0 = \beta_0 / \sigma^2\). By using the same method to transform the causal constraints, we find that the causal constraints are non-convex for the power optimization variable [5]. In order to facilitate the solution, we need to convert the above non-convex constraints into convex constraints. By introducing the relaxation variable \(t[n]\), transform the causal constraints into:

\[
\sum_{i=1}^{n} t_i[i] \leq \sum_{i=1}^{n-1} \log_2 \left( 1 + P_i[i] \alpha_{i,i}[i] \right), \forall n
\]

(12)

2.2.2 Relay trajectory optimization of multiple UAVs

The optimal solution of the above sub-optimization problem is taken as the fixed condition of the sub-optimization problem, that is, the transmission power of the signal source and UAV relay is known, so only the flight trajectory of UAV relay needs to be optimized. The sub-optimization problem can be expressed as:

\[
\max_{l_k, l_h} \sum_{n=1}^{N} \left( \log_2 \left( 1 + \frac{p_{K}'}{H^2 + \|q_D - w_k[n]\|^2} \right) \right), \forall k
\]

(13)

\[
\eta_k = p_{K}' \gamma_0, \quad p_{m}' = p_{m} \gamma_0
\]

The analysis shows that the target problem is non-convex for trajectory variables, so it cannot be solved directly. To solve the non-convexity of the above problem, we introduce the relaxation variable \(\eta[n], l[n], h[n]\). Therefore, the above optimization problems can be translated into:

\[
\max_{w_k, \eta_k, l_k, h_k} \sum_{n=1}^{N} \eta_k[n], \forall k
\]

(14)

\[
\text{s.t.} \log_2 \left( 1 + \frac{p_{K}'}{l_{K,D}[n] h_{m,D}} \right) \geq \eta_k[n], \forall n
\]

(15)

The constraint condition is also non-convex for trajectory optimization variables, so relaxation variables are introduced into the constraint condition \(d[n]\). Convert it to:

\[
\sum p_{m} d_{m,k}^{-1}[n] + 1 \leq h_{m,k}[n], \forall m,k,n
\]

(16)

\[
d_{m,k}[n] \geq H^2, \forall m,k,n
\]

(17)

\[
H^2 + \|w_k[n] - q_m\|^2 \geq d_{m,k}[n], \forall m,k,n
\]

(18)

Through judgment, we find that the constraint condition is non-convex. Therefore, combined with the constraint condition (1), it is transformed into:
\[-(x_k[n] - x_{em} - \Delta x_m)^2 - (y_k[n] - y_{em} - \Delta y_m)^2 - H^2 \]

(19)

According to the known quadratic inequality (2), the solution of the unknown quadratic inequality (19) can be derived, namely the S-Procedure theory \(\zeta_m[n] \geq 0\), satisfy:

\[
\Phi(x_k[n], y_k[n], d_{m,k}[n], \zeta_m[n]) \geq 0
\]

(20)

Where

\[
c_m[n] = x_k^2[n] - 2x_{em}x_k[n] + x_{em}^2 + y_k^2[n] - 2y_{em}y_k[n]
\]

(21)

Since the quadratic term in (19) is nonlinear, the constraint condition is non-convex. Approximate expression of quadratic term in (19) by first-order Taylor expansion can be obtained:

\[
\tilde{c}_m[n] = -x_k'\bar{x}_k[n]^2 + 2x_k'\bar{x}_k[n]x_{k}[n] - 2x_{em}x_k[n] + x_{em}^2 - y_k'\bar{y}_k[n]^2 + 2y_k'\bar{y}_k[n]y_{k}[n] - 2y_{em}y_k[n] + y_{em}^2 + H^2 - d_{m,k}[n]
\]

(22)

Where

\[
x_k'[n] \geq -x_k'[n]^2 + 2x_k'[n]x_k[n],
\]

(23)

\[
y_k'[n] \geq -y_k'[n]^2 + 2y_k'[n]y_k[n],
\]

(24)

\(x_k'[n], y_k'[n]\) Represents a feasible solution satisfying the constraint. The convex constraint condition can be obtained by substituting this condition into (48). At this point, we get the sub-optimization problem whose optimization problem and constraint conditions are both convex. Therefore, CVX tool can be used to obtain the optimal solution satisfying the above constraints, namely the flight trajectory of UAV relay. Then the result is taken as the known condition of the first sub-optimization problem, and the two sub-optimization problems are solved iteratively until the optimization result converges. Finally, the joint optimal solution of the original optimization problem can be obtained.

3. Results

We use Matlab and CVX simulation tools to verify the effectiveness of the design scheme based on physical layer security technology when there are interference sources in the communication system. In order to more intuitively see the advantages of the joint optimization scheme, we compared the communication performance of several different deployment schemes under the same communication model. These uav deployment options are described below:

1. Joint optimization scheme of multi-UAV: multi-hop UAV relay is used for information transmission, and the transmitting power of signal source, transmitting power of UAV relay and flight track are jointly optimized during flight;

2. Multi-UAV trajectory optimization only scheme: Multi-hop UAV relay is used for information transmission, in which signal source and UAV relay send information at constant transmitting power during the execution of the task, and only the flight trajectory of UAV relay is optimized;

3. Power-only optimization scheme of multiple UAVs: Information transmission is carried out through multi-hop UAVs relay, in which the flight path of UAV relay is fixed, that is, uav relay flies uniformly from the initial position to a fixed position, and then flies uniformly back to the destination position, and only the transmission power of signal source and UAV relay is optimized;

4. Joint optimization scheme of single UAV: single UAV relay is used for information transmission, and the transmitting power of signal source and the transmitting power and flight track of UAV relay are jointly optimized.

It is assumed that there are two UAV relays and two unknown interference sources in the communication model with interference sources, and the safety performance of the communication system is...
analyzed by comparing the flight track of UAV relays and the distribution of transmitting power and the change of the average receiving rate of the target point under the above deployment schemes. Table 4-1 lists the simulation parameters.

| Simulation parameter                          | Specific value       |
|-----------------------------------------------|----------------------|
| The estimated radius of interference source   | $Q_1 = 30m$, $Q_2 = 50m$ |
| Fixed flight altitude for uav relay           | $H = 100m$           |
| The minimum distance between any two drone relays | $d_{min} = 10m$   |
| The average and peak transmission power of the signal source | $P_{S_{ave}} = 50mW$, $P_{S_{max}} = 4P_{S_{ave}}$ |
| Average and peak transmission power of uav relay | $P_{UAV_{ave}} = 50mW$, $P_{UAV_{max}} = 4P_{UAV_{ave}}$ |
| Time of flight clearance                       | $d_i = 5s$           |
| The maximum horizontal flight speed of the uav | $v_{max} = 10m/s$    |
| Reference channel gain                         | $\beta_0 = -40dBm$  |
| Noise power                                    | $\sigma^2 = -110dBm$ |
| Path loss index of ground fading channel      | $\kappa = 3$        |
| Accuracy of iterative convergence              | $\epsilon = 10^{-3}$ |

Assuming that the signal source and the target point are located at (0,0,0) and (1400,0,0) respectively, we use two uav relays to transmit information between them, in which the start position and end position of the uav relay are located at (700,400,100) and (700,-400,100) respectively. In the process of experiment, we consider the situation where the interference source is located in different positions, where the interference source is located near the emission source and the target point. By observing the flight track of UAV relay when $N=50$, that is, the flight time is 250s, we analyze the influence of different interference source positions on the flight track and secure communication performance of UAV relay.

In Figure 2 shows the flight track of two UAVs when two interference sources are located near the signal source and the flight time is 250s. When $T=250s$, uav relay 1 in scheme (1) is farther from signal source and interference source than scheme (2) and scheme (4). However, uav relay 1 in scheme (1) flies to signal source earlier and closer to signal source when it flies to destination position, and can receive information from signal source as much as possible. Compared with (2), UAV trunk 2 is farther away from the interference source at the beginning, in order to reduce the influence of interference source on UAV trunk 2 during transmission from UAV trunk 1 to UAV trunk 2. In scheme (2), since the transmitting power of signal source and UAV relay is fixed, UAV relay can only improve the transmission rate of information by being close to signal source and target point, and the receiving end is far away from interference source to reduce the influence of interference source. In scheme (4), THE UAV relay is closer to the signal source than the target point. This is because the interference source is near the signal source, which has a great influence on the reception of uav relay. Therefore, the UAV relay is closer to the signal source to receive more information. However, in scheme (3), the average impact during flight does not change much, so the performance gain brought by the increase of flight time is not obvious.

Figure 3 shows the flight track of the two UAVs when the two interference sources are located near the target point and the flight time is 250s. When $T=250s$, uav relay 1 in schemes (1) and (2) flies directly to the signal source and can reach the position closer to the signal source. In scheme (1), UAV relay 2 can reach a position closer to the target point compared with scheme (2). This is because in
scheme (2), UAV relay 2 is greatly affected by interference sources when flying to the target point, so it receives less information from UAV relay 1. In scheme (4), uav relay will also be closer to signal source and target point, but cannot reach the similar position in scheme (1) and scheme (2). However, in scheme (3), UAV relay still flies at a constant speed and a fixed track. In this process, the influence of interference sources on UAV relay does not change much.

Next, we further analyze the characteristics of the joint optimization scheme by combining the transmission power distribution of the signal source and uav relay. Figure 4-5 shows the transmission power distribution of the signal source and uav relay when the transmission power of the interference source is 0.01W, the flight time is 250s, and the interference source is located near the signal source and the target point respectively.

When the interference source is located near the signal source, the signal source transmits information to UAV relay 1 within 0~200s. After that, the signal source hardly sends any information. At this time, UA V Relay 1 is the furthest away from the signal source. However, the information transmitted from UAV relay 1 to UAV relay 2 is mainly concentrated between 60~130s and 180~200s, indicating that UA V relay mainly transmits information when the distance is relatively close. The process of sending information from UAV trunk 1 to UAV trunk 2 is mainly carried out at a location far away from the interference source. The change of transmission power distribution indicates that uav trunk is interfered to different degrees at different locations.

When the interference source is located near the target point, the main difference from the previous situation lies in the process of sending information from UAV relay 1 to UAV relay 2. The reason for the difference is that uav relay is affected by different interference signals at different positions, and the transmission process is mainly concentrated at the position with the least interference influence. In conclusion, (1) the scheme can jointly optimize the flight trajectory and transmitting power under the condition of minimal interference, thus significantly improving the safe reception performance of the system.
In order to analyze the change of system communication performance more directly, we take the average receiving rate of the target point as an index to evaluate system security. Figure 4-3 shows the change of the average receiving rate of the target point with time when the interference power is 0.01W and the interference source is located near the signal source and the target point.

In general, each scheme under the target receives an average rate increases with the increase of time, always receives an average of one (1) plan rate solutions than (2), (3) and (4), and (3) scheme in the target receives an average rate of change over time increases slightly, because flying unmanned aerial vehicle (uav) always keeps uniform, Therefore, there is little difference in the average influence of interference sources during the whole flight. When the interference source is near the signal source, scheme (3) is superior to scheme (2) before 170s, and scheme (3) is superior to scheme (4) before 250s, because the position of uav relay in scheme (3) is closer to the signal source and target point.

When the flight time of uav is 450s, when the transmitting power of the interference source is 0.01W and the interference source is located near the signal source, the average safe receiving rate of the target point under scheme (1) increases by 0.23 BPS /Hz and 1.2 BPS /Hz respectively compared with scheme (2) and Scheme (3). When the interference source is located near the target point, (1) Compared with the other two schemes, the scheme improves 0.4 BPS /Hz and 1.45 BPS /Hz respectively. Compared with scheme (4), scheme (1) using multi-UAV relay improves 0.48 BPS /Hz and 0.6 BPS /Hz respectively when the interference source is near the signal source and the target point. Moreover, it is found that when the interference source is located near the signal source, the average safe receiving rate of the target point under (1) scheme decreases by 0.27 BPS /Hz, indicating that the interference source has a great influence on secure communication at this time.
4. conclusion

In this article, we consider the use in multiple hops unmanned aerial vehicle (uav) trunking communication system, the condition of the position of the unknown interference source, we use the design scheme based on the physical layer security technology, to achieve a more secure and efficient communication, through the joint optimization of signal source and drones relay transmission power and trajectories of the relay to reduce the influence of interference sources of wireless communication. Firstly, we construct the optimization problem about secure receive rate, and then obtain the joint optimal solution of the problem through iterative optimization method. Finally, simulation proves that the joint optimization scheme can achieve better performance than other deployment schemes.

In this system, multi-uav relay can effectively increase the distance of information transmission, and the cooperation of multi-UA V can effectively transmit information and reduce interference. When there are interference sources in the system, the average safe receiving rate of the target point is improved by 15%~20% when two UAV relays are used compared with the single UAV relay with the same joint optimization scheme. We also consider the influence of different interference sources on secure communication. When the interference source is near the signal source, the average secure reception rate of the target point under the joint optimization scheme is about 10% lower than that when the interference source is near the target point. Therefore, when the interference source is located near the target point, the joint optimization scheme can achieve more secure communication.

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