Securing Mobile Multiuser Transmissions with UAVs in the Presence of Multiple Eavesdroppers

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Abstract—This paper analyzes the problem of securing the transmissions of multiple mobile users against eavesdropping attacks. We propose and optimize the deployment of a single unmanned aerial vehicle (UAV), which serves as an aerial relay (AR) between the user cluster and the base station. The focus is on maximizing the secrecy energy efficiency by jointly optimizing the uplink transmission powers of the ground users and the position of the UAV. The joint optimization problem is nonconvex; therefore we split it into two subproblems and solve them using an iterative algorithm.

Index Words--AR, cellular communications, secrecy rate, security, UAV.

I. INTRODUCTION

The worldwide deployment of 4G long-term evolution (LTE) and now 5G New Radio (NR) networks and the increasing number of vertical industries that those networks support require secure and reliable communications. Unmanned aerial vehicles (UAVs) will be fully integrated into cellular networks and will be able to assist 5G and beyond networks [1]. UAVs come in many forms. They have flexible mobility patterns, can hover, be tethered, and establish line of sight (LoS) connectivity with ground users at low deployment costs. An emerging application for UAVs is the use of rapidly deployable aerial support nodes that can enhance the security of terrestrial or aerial wireless networks [2].

This paper focuses on the security of the cellular radio access network and, in particular, the privacy of broadband transmissions. We analyze the feasibility of using a single UAV to improve the security of several ground cellular network users against eavesdropping. Eavesdropping is a fundamental attack, where the eavesdropper is a radio receiver that illegitimately captures information transmitted over the air. This attack can compromise the privacy of sensitive data, missions, or systems. It can also facilitate effective follow-up attacks on the data integrity or service availability, among others.

UAVs have been considered as wireless support nodes for improving the physical layer security. This includes the deployment of aerial relays (ARs) and jammers for protecting a single terrestrial link against a ground or aerial eavesdropper [3]. Reference [4] aims at protecting a single UAV-to-ground transmission against static eavesdropping attacks by optimizing the UAV trajectory and transmission power of the UAV. The authors of [5] propose a similar technique to enhance the secrecy rate of UAV-to-ground communications under a single static eavesdropping attack at a known location. The work presented in [6] secures the downlink (DL) transmission from an aerial base station (BS) to multiple ground users in a time division multiple access manner while another UAV is jamming the signals. It jointly optimizes the user scheduling, transmission powers, and the UAV trajectory. Similarly, [7] designs an optimization problem for the same environment, but for frequency division multiple access.

Prior research has considered the UAV as an AR for securing a single link against eavesdropping. Mobile and vehicular users are assumed in [8] and [9], which explore the benefits of a single AR per user. Such solutions are not scalable. References [6] and [7] address the multiuser scenario, but with static users. There is a research gap in analyzing the scalability performance of an AR supporting multiple mobile users against multiple eavesdroppers. This paper therefore proposes and analyzes a practical UAV positioning and multiuser power control (PC) scheme to maximize the secrecy energy efficiency (SEE) for efficient and secure multiuser broadband communications. Our results show that a single AR can effectively improve the SEE of a cluster of mobile users.

We present the system model, problem formulation and our iterative solution in Sections II, III, and IV. Section V provides the numerical results. Section VI derives the conclusions.

II. SYSTEM MODEL

Fig. 1 illustrates the scenario considered in this work. A cluster of mobile ground users communicates with a BS in the presence of terrestrial eavesdroppers. The active users in the cluster are randomly distributed. The UAV is positioned to support the users by relaying their data streams. Without loss of generality, in this paper we model and analyze the uplink (UL) channel. The same principles can be applied for the DL.

The set of $M$ users in the cluster and the set of $K$ eavesdroppers are denoted as $V = \{V_i|i = 1, 2, ..., M\}$ and $E = \{E_j|j = 1, 2, ..., K\}$, respectively. We define the location of the UAV relay, the eavesdropper, and the $i$th user in the 3D Cartesian coordinate system as $(x_u, y_u, z_u)$, $(x_j, y_j, z_j)$, and $(x_i, y_i, z_i)$. The work presented in [6] secures the downlink (DL) transmission from an aerial base station (BS) to multiple ground users.
transmits signal \( s_i \) with power \( P_i \) is defined as
\[
r_u = \sqrt{P_i g_{iu} s_i + n_i},
\]
where \( g_{iu} \) is the air-to-ground (A2G) channel power gain between user \( V_i \) and the UAV, and \( n_i \) denotes the additive white Gaussian noise (AWGN) of zero mean and \( \sigma^2 \) variance. Measurements have shown that the LoS channel model is a good approximation in rural areas above 80 m [10]. The channel gain has a path loss exponent of two and can be written as
\[
g_{iu}[n] = \beta_0 d_{iu}^{-2}[n]
\]
where \( \beta_0 \) is the channel gain at the reference point of \( d_0 = 1 \) m which is contingent on the transmitter and receiver antenna gains and the carrier frequency. Parameter \( d_{iu}[n] \) represents the distance between the \( i \)th user and the UAV.

The capacity of the channel between user \( V_i \) and the UAV in time slot \( n \) is given as
\[
C_{iu}[n] = \log_2 \left( 1 + \frac{P_i g_{iu}[n]}{\sigma^2} \right) = \log_2 \left( 1 + \frac{\lambda_0 P_i}{d_{iu}^2[n]} \right),
\]
where \( \lambda_0 = \beta_0 / \sigma^2 \) is the signal-to-noise ratio (SNR) at the reference point.

B. Wiretap Channel

Because the UAV is in the air and can often establish an LoS link with the BS, beamforming and PC can be effectively employed to focus the radio frequency (RF) transmission between the BS and UAV. On the other hand, a UE may have a single transmit antenna and, thus, its UL transmission will not be focused. Assuming ground eavesdroppers, here we therefore consider the user-UAV link being the dominant eavesdropping channel.

The transmitted signal from user \( V_i \) is overheard by eavesdropper \( E_j \), which receives
\[
r_j = \sqrt{P_i w_{ij} s_i + n_j},
\]
where \( n_j \) denotes the AWGN at the eavesdropper \( E_j \). Because users and eavesdroppers are on the ground, the path loss exponent is assumed to be four. The ground-to-ground (G2G) channel gain between user \( V_i \) and eavesdropper \( E_j \) in time slot \( n \) can then be modeled as
\[
w_{ij}[n] = \beta_0 d_{ij}^{-4}[n]
\]
where \( d_{ij}[n] \) is the distance between the \( i \)th user and the \( j \)th eavesdropper in the \( n \)th time slot. The corresponding capacity is
\[
C_{ij}[n] = \log_2 \left( 1 + \frac{P_i [n] w_{ij}[n]}{\sigma^2} \right) = \log_2 \left( 1 + \frac{\lambda_0 P_i}{d_{ij}^2[n]} \right),
\]
C. Secrecy Capacity Metric

The common metric to evaluate the influence of eavesdropping and the performance of mitigation techniques is the secrecy capacity. The secrecy capacity is calculated as the difference between the legitimate and the wiretap channel capacities and corresponds to the rate at which no data will be decoded by the eavesdropper [11]. The average secrecy capacity per cluster position over \( N \) radio time slots with \( M \) users and \( E \) eavesdroppers and one AR is then obtained as
\[
C_{sec} = \frac{1}{N} \sum_{n=1}^{N} \left[ \sum_{i=1}^{M} C_{iu} - \max_{j \in E} \sum_{i=1}^{M} C_{ij}[n] \right]^{+},
\]
where \( [x]^{+} = \max(x, 0) \)

III. Problem Formulation

The objective of this paper is maximizing the average secrecy rate \( C_{sec} \) by optimizing the AR position and transmission power.

In order to have a short distance to the affected users with strong LoS connections, the UAV position constraint is formulated as follows:
\[
\sqrt{(x_u[n] - x_{center}[n])^2 + (y_u[n] - y_{center}[n])^2} \leq R, \forall n,
\]
where \( x_{center}[n] \) and \( y_{center}[n] \) are the center coordinates of the mobile cluster at time slot \( n \). We introduce the average transmission power \( \bar{P} \) and the peak transmission power \( P_{max} \), where \( \bar{P} \leq P_{max} \). The UL transmission power constraint for each user is
\[
\frac{1}{N} \sum_{n=1}^{N} P[n] \leq \bar{P}, \quad 0 \leq P[n] \leq P_{max}, \forall n.
\]

The optimization problem can now be written as
\[
(P1): \max_{x_u, y_u, \bar{P}} \frac{1}{N} \sum_{n=1}^{N} \left[ \sum_{i=1}^{M} \log_2 \left( 1 + \frac{\lambda_0 P_i}{d_{iu}^2[n]} \right) \right]^{+}
\]
\[\quad - \max_{j \in E} \sum_{i=1}^{M} \log_2 \left( 1 + \frac{\lambda_0 P_i}{d_{ij}^2[n]} \right)^{+},
\]
s.t. (8), (9), (10).

IV. Iterative Solution

The objective function is non-convex with respect the optimization parameters \( x_u, y_u \), and \( P \). In addition, the \([\cdot]^{+}\) operator creates a non-smooth objective function.

Lemma 1: Problem P1 can be reformulated as a new optimization problem P2 with the same optimal solution.
\[(P2): \max_{x_u, y_u, P} \frac{1}{N} \sum_{n=1}^{N} \left[ \sum_{i=1}^{M} \log_2 \left( 1 + \frac{\lambda_0 P_i[n]}{d_{iu}^2[n]} \right) \right], \]
\[\text{s.t. } (8), (9), (10).\]

Proof of Lemma 1: Let $\xi_1^*$ and $\xi_2^*$ be the optimal solutions for problems (11) and (12), respectively, and because $[v]^+ \geq [v]$, $\xi_1^* \geq \xi_2^*$. The optimal solution of (11) $\xi_1^* = (x_u^*, y_u^*, P^*)$, where $x_u^* = [x_u^*[1], x_u^*[2], \ldots, x_u^*[N]]^\top$, $y_u^* = [y_u^*[1], y_u^*[2], \ldots, y_u^*[N]]^\top$, and $P^* = [P^*[1], P^*[2], \ldots, P^*[N]]^\top$. We define $\tau(x_u[n], y_u[n], P[n]) = \sum_{i=1}^{M} \log_2 \left( 1 + \frac{\lambda_0 P_i[n]}{d_{iu}^2[n]} \right) - \max_{j \in E} \sum_{i=1}^{M} \log_2 \left( 1 + \frac{\lambda_0 P_i[n]}{d_{ij}^2[n]} \right).$ (13)

Let $\tilde{P} = (\tilde{x}_u, \tilde{y}_u, \tilde{P})$ represent the feasible values that are constructed while solving (12), where $\tilde{x}_u = x_u^*, \tilde{y}_u = y_u^*$ and $\tilde{P}[n]$ can be computed as follows:

\[
\tilde{P}[n] = \begin{cases} 
P^*[n] & \tau(x_u[n], y_u[n], P[n]) \geq 0, \\
0 & \tau(x_u[n], y_u[n], P[n]) < 0,
\end{cases}
\]

(14)

In other words, the UL transmission power is set to zero if (13) is negative. This will maximize (12), because the inner term of (12), i.e. (13), is 0 instead of being negative for a certain $n$, where an eavesdropper drops a higher reception rate than the AR. This is equivalent to using the $[.]^+$ operator in (11). The constructed final solution $\tilde{v}$ based on $(\tilde{x}_u, \tilde{y}_u, \tilde{P})$ ensures that $\tilde{v} = \xi_1^*$. Then, $(\tilde{x}_u, \tilde{y}_u, \tilde{P})$ represents a feasible solution for (12), consequently $\xi_2^* \geq \tilde{v}$ and, therefore, $\xi_2^* \geq \xi_1^*$. Since the premise at the beginning of the proof was that $\xi_1^* \geq \xi_2^*$, the equality holds, i.e. $\xi_1^* = \xi_2^*$, proving Lemma 1.

The transformation from problem P1 to problem P2 eliminates the non-smoothness, but P2 is still non-convex. We therefore propose an iterative algorithm for solving P2. It is derived from the block coordinate descent strategy. In particular, we split the problem into two subproblems by separating the optimization variables in two blocks. The first subproblem optimizes the transmission powers with respect to a given UAV position. The second subproblem aims at finding the optimal UAV position for the given transmission powers. The solution of one subproblem is applied to the other subproblem, iteratively until convergence.

A. Subproblem P2.I: Transmission Power Optimization
We apply $\log_2(z) = \ln(z) / \ln(2)$ to define the optimization subproblem P2.I as

\[
(P2.I) : \max_{x_u, y_u, P} \frac{1}{N} \sum_{n=1}^{N} \left[ \sum_{i=1}^{M} \ln(1 + \mu_n P_i[n]) \right] - \max_{j \in E} \sum_{i=1}^{M} \ln(1 + \eta_n P_i[n]),
\]
\[\text{s.t. } (9), (10),\]

where

\[
\mu_n = \frac{(x_i[n] - x_u[n])^2 + (y_i[n] - y_u[n])^2 + (z_i[n] - z_u[n])^2}{\lambda_0} \\
\eta_n = \frac{(x_i[n] - x_u[n])^2 + (y_i[n] - y_u[n])^2 + (z_i[n] - z_j[n])^2}{\lambda_0}.
\]

B. Subproblem P2.II: UAV Position Optimization
The second subproblem of problem P2 optimizes the UAV position. It can be formulated as

\[
(P2.II) : \max_{x_u, y_u, \psi} \frac{1}{N} \sum_{n=1}^{N} \left[ \sum_{i=1}^{M} \log_2 \left( 1 + \frac{\hat{P}_i[n]}{d_{iu}^2[n]} \right) \right] - \max_{j \in E} \sum_{i=1}^{M} \log_2 \left( 1 + \frac{\hat{P}_i[n]}{d_{ij}^2[n]} \right),
\]
\[\text{s.t. } (8),\]

where $\hat{P}_i = \lambda_0 P_i[n]$.

Here we optimize only the AR position. Hence, the focus is on maximizing the capacity between the ground users and the UAV. In order to solve this subproblem, which is a non-concave function with respect to $x_u$ and $y_u$, we add a slack variable $\psi = [\psi[1], \ldots, \psi[N]]^\top$. The optimization problem can then be reformulated as

\[
(P2.II) : \max_{x_u, y_u, \psi} \frac{1}{N} \sum_{n=1}^{N} \left[ \sum_{i=1}^{M} \log_2 \left( 1 + \frac{\hat{P}_i[n]}{\psi[n]} \right) \right] - \max_{j \in E} \sum_{i=1}^{M} \log_2 \left( 1 + \frac{\hat{P}_i[n]}{d_{ij}^2[n]} \right),
\]
\[\text{s.t.}\]
ψ[n] = −x_2^n[n] + 2x_i[n]x_u[n] + x_u(fea)[n] − 2x_u(fea)[n]x_u[n]
− y_2^n[n] + 2y_i[n]y_u[n] + y_u(fea)[n] − 2y_u(fea)[n]y_u[n]
− z_i^n[n] + 2z_i[n]H - H^2 ≤ 0, \forall n.
(22.b)

ψ[n] ≥ 0, \forall n.
(22.c)

The equality in (22.b) and (22.c) shall be satisfied for the optimal solution. If this is not the case, then the slack variable \( \psi[n] \) can be increased until an improvement in the objective function is achieved. As a result, we can consider that the ideal result of (22) will be the same for (21).

In the process of finding the optimal solution for (22), we must consider the terms \( -x_2^n[n] \) and \( -y_2^n[n] \) that conceive the non-convexity. Therefore, we employ an iterative algorithm that uses the successive convex optimization method for developing an approximate solution for (22) by maximizing the concave lower bound of the objective function within the convex feasible region.

First, we introduce \( x_{u\text{(fea)}} \triangleq [x_{u\text{(fea)}}[1], \ldots, x_{u\text{(fea)}}[N]] \), \( y_{u\text{(fea)}} \triangleq [y_{u\text{(fea)}}[1], \ldots, y_{u\text{(fea)}}[N]]^\dagger \), and \( \psi_{\text{(fea)}} \triangleq [\psi_{\text{(fea)}}[1], \ldots, \psi_{\text{(fea)}}[N]] \), where this initial point \( (x_{u\text{(fea)}}, y_{u\text{(fea)}}, \psi_{\text{(fea)}}) \) is feasible to (22). By taking into consideration that \( x_2^n[n] \) and \( y_2^n[n] \) are concave functions, their first-order Taylor expansions at \( x_{u\text{(fea)}}, y_{u\text{(fea)}}, \) and \( \psi_{\text{(fea)}} \) are global over-estimators. Therefore, the next step will be calculating the first-order Taylor expansions at \( x_{u\text{(fea)}}, y_{u\text{(fea)}}, \) and \( \psi_{\text{(fea)}} \) for the following terms

\[
\sum_{i=1}^{M} \log_2 \left( 1 + \frac{P_i}{\psi[n]} \right),
\]

\[
-x_2^n[n], \quad \text{and} \quad -y_2^n[n],
\]

respectively:

\[
\sum_{i=1}^{M} \log_2 \left( 1 + \frac{P_i}{\psi[n]} \right) \geq \sum_{i=1}^{M} \log_2 \left( 1 + \frac{P_i}{\psi_{\text{(fea)}}[n]} \right) - \ln 2(\psi_{\text{(fea)}}[n] + \hat{P}_i(\psi[n] - \psi_{\text{(fea)}}[n])),
\]

\[
\hat{P}_i(\psi[n] - \psi_{\text{(fea)}}[n]),
\]

\[
-x_2^n[n] \leq x_{u\text{(fea)}}[n] - 2x_{u\text{(fea)}}[n]x_u[n],
\]

\[
-y_2^n[n] \leq y_{u\text{(fea)}}[n] - 2y_{u\text{(fea)}}[n]y_u[n],
\]

As a result, (22.a) and its constraint (22.b) can be reformulated as

\[
(P2.II) : \max_{x_u, y_u, \psi} \frac{1}{N} \sum_{n=1}^{N} \left[ \sum_{i=1}^{M} \ln 2(\psi_{\text{(fea)}}[n] + \hat{P}_i(\psi[n])) \right]
\]

s.t.
\[
\psi[n] - x_2^n[n] + 2x_i[n]x_u[n] + x_u(fea)[n] - 2x_u(fea)[n]x_u[n]
\]

\[
- y_2^n[n] + 2y_i[n]y_u[n] + y_u(fea)[n] - 2y_u(fea)[n]y_u[n]
\]

\[
- z_i^n[n] + 2z_i[n]H - H^2 ≤ 0, \forall n,
\]

\[
\psi[n] ≥ 0, \forall n.
\]
Algorithm 1: Proposed algorithm for optimizing the transmission power and UAV position.

1. Initialize $P^{(0)}, x_u^{(0)}, y_u^{(0)}$, and the initial slack variable $\psi^{(0)}$ to feasible values and set $j = 0$;
2. Calculate $C^{(0)} = f_{P2}(P^{(0)}, x_u^{(0)}, y_u^{(0)})$ according to (12);
3. while $C^{(j)} - C^{(j-1)} \leq \chi$
   4. With given $P^{(j-1)}$, set the new feasible points $x_u^{(j)}(\psi_u) = x_u^{(j-1)}$, $y_u(\psi_u) = y_u^{(j-1)}$, and $\psi^{(j)} = \psi^{(j-1)}$;
   5. Calculate the new trajectory update $(x_u^{(j)}, y_u^{(j)})$ and the slack variable $\psi^{(j)}$ according to (26);
   6. Solve equation (19) with the obtained trajectory $(x_u^{(j)}, y_u^{(j)})$ to calculate the updated transmission powers $P^{(j)}$;
   7. Calculate the new $C^{(j)} = f_{P2}(P^{(j)}, x_u^{(j)}, y_u^{(j)})$ according to (12);
   8. $j \leftarrow j + 1$
9. Result: Optimal $P, x_u$ and $y_u$

Fig. 2 illustrates the SEE results at the different locations along the traveled path of the user cluster. The results show the cases where the eavesdroppers attack a cluster of one, two, or four mobile UEs.

The curves show that the SEE performances when applying the proposed joint optimization method are nearly identical for a single, two, or four UEs that are served by the AR. Overall, the proposed technique shows outstanding performance in terms of SEE when compared to no relaying and superior performance when compared to other UAV positions. Additional simulations with more UEs in the cluster show similar results. This verifies the scalability of the AR assisted technique as an effective mitigation strategy against eavesdropping.

Fig. 3 shows the convergence behavior of the iterative algorithm for four UEs under attack and two UAV heights. The corresponding curves for one and two UEs in the cluster are nearly identical and are therefore omitted. The initial SEE is nearly 6 bps/Hz/W and after 130 iterations, the algorithm converges at 10 and 8 bps/Hz/W for UAV heights of 80 and 160 m, respectively.

Tables I provides the simulation parameters.
for this purpose, but has not analyzed the scalability of ARs and maneuverability in the 3D space, LoS links with ground nodes, and their low cost. Research has considered ARs and the SEE by almost 50% in the tight attack zone between the two eavesdroppers.

The obtained results confirm that combining the optimization of the transmission powers of ground users and the AR trajectory can significantly improve the UE power efficiency and the SEE by almost 50% in the tight attack zone between the two eavesdroppers.

VI. CONCLUSIONS

UAV-based ARs have been proposed as a mitigation technique against eavesdropping because of their high mobility and maneuverability in the 3D space, LoS links with ground nodes, and their low cost. Research has considered ARs for this purpose, but has not analyzed the scalability of a UAV for supporting multiple mobile users. Because of its importance for practical deployments, this paper has studied this aspect and formulated and solved a problem that optimizes UE transmission powers and UAV positioning. The obtained results and key findings show that the use of a single UAV as an AR is an efficient and scalable mitigation scheme for multiple mobile users against distributed eavesdroppers. Future work will assess the secrecy of the BS-UAV link in different settings as well as analyze the relation of the cluster radius, number of UEs, and adaptive UAV altitudes with their corresponding channel models on the optimal AR deployment. We will also validate the proposed techniques on suitable research platforms, such as the Aerial Experimentation and Research Platform for Advanced Wireless (AERPAW) [15].

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