Exploiting Physical-Layer Security for Multiuser Multicarrier Computation Offloading

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Abstract—This letter considers a mobile edge computing (MEC) system with one access point (AP) serving multiple users over a multicarrier channel, in the presence of a malicious eavesdropper. In this system, each user can execute the respective computation tasks by partitioning them into two parts, which are computed locally and offloaded to AP, respectively. We exploit the physical-layer security to secure the multiuser computation offloading from being overheard by the eavesdropper. Under this setup, we minimize the weighted sum-energy consumption for these users, subject to the newly imposed secrecy offloading rate constraints and the computation latency constraints, by jointly optimizing their computation and communication resource allocations. We propose an efficient algorithm to solve this problem.

Index Terms—Mobile edge computing (MEC), multiuser computation offloading, physical-layer security, optimization.

I. INTRODUCTION

Mobile edge computing (MEC) has emerged as a promising technique to enhance the computation capacity and energy efficiency of wireless devices, for enabling various computation-intensive and latency-critical Internet-of-things (IoT) applications [1]. By deploying MEC servers at the network edge such as access points (APs), IoT devices can wirelessly offload the computation-heavy tasks to APs for efficient remote execution (see, e.g., [2]–[6]). Despite the benefits, the wireless task offloading introduces new data security problems for wireless IoT devices. Due to the broadcast nature of wireless communications, the computation tasks offloaded from these devices are likely to be overheard by malicious attackers nearby, which may decode such information for launching security attacks. For the success of MEC, it is crucial to keep the confidentiality of the task offloading against eavesdropping attacks.

Physical-layer security has emerged as a viable solution to ensure perfectly secured wireless communications against eavesdropping attacks, provided that (partial) channel state information (CSI) of the eavesdroppers is available at the legitimate users (see, e.g., [7]–[9]). In physical-layer security, the key design objective is to maximize the so-called secrecy rate, i.e., the secure communication rate under the condition that the eavesdroppers cannot overhear any information.

In this letter, we propose to employ the physical-layer security to secure the wireless computation offloading in MEC. We particularly focus on a multiuser multicarrier (e.g., orthogonal frequency-division multiple access (OFDMA)) system as shown in Fig. 1, in which a single AP (with an MEC server integrated) serves multiple users for their computation offloading, in the presence of a malicious eavesdropper. Each user can partition the computation tasks into two parts, which are

Fig. 1. The MEC system model with secure multiuser computation offloading over a multicarrier channel, in the presence of a malicious eavesdropper. Computation-heavy tasks to APs for efficient remote execution can be computed locally and securely offloaded to AP, respectively.

II. SYSTEM MODEL

As shown in Fig. 1, we consider an MEC system with a single AP (with an MEC server integrated) and $K > 1$ users, in the presence of a malicious eavesdropper [10]. Let $K = \{1, \ldots, K\}$ denote the set of users. All nodes are equipped with a single antenna. We focus on a particular time block with duration $T$, during which each user $k \in K$ needs to execute the computation tasks with $L_k > 0$ input bits. We consider the data partition task model for partial offloading, in which each task-input bit can be viewed as an independent sub-task. Therefore, user $k$ can partition the respective tasks into two portions with $l_k$ and $(L_k - l_k)$ input bits, which are locally computed at the user itself and securely offloaded to the AP over a multicarrier

1Our results are extendible to the case with more than one eavesdropper, in which each user’s achievable secrecy rate for offloading should be modified based on that in the so-called compound wire-tap channels with multiple eavesdroppers (see, e.g., [10]).
channel for remote execution, respectively. We consider a quasi-static subcarrier channel model, in which the wireless channels remain constant over each subcarrier within this block. Let \( N \) denote the number of subcarriers in this system. For each subcarrier \( n \in \mathcal{N} = \{1, \ldots, N\} \), let \( h_{k,n} \) and \( g_{k,n} \) denote the channel power gains from user \( k \) to the AP and the eavesdropper, respectively. We assume that the AP perfectly knows the CSI of \( h_{k,n} \)'s and the computation information of all users, but only partially knows that of \( g_{k,n} \)’s. As commonly adopted in the physical-layer security literature \([12, 13]\), we consider the deterministic CSI uncertainty model for \( g_{k,n} \)'s, where \( \tilde{g}_{k,n} = g_{k,n} + \Delta g_{k,n}, k \in \mathcal{K}, n \in \mathcal{N} \). Here, \( \Delta g_{k,n} \) denotes the estimated CSI of \( g_{k,n} \) at the AP and \( \Delta g_{k,n} \) denotes the estimation error that is bounded by a possible value \( \epsilon \geq 0 \) (also know by the AP) as \(|\Delta g_{k,n}| \leq \epsilon \).

As for the local computing of the \( l_k \) input bits at each user \( k \in \mathcal{K} \), let \( C_k \) denote the number of CPU cycles required for computing one task-input bit (or each independent sub-task). Accordingly, the total number of CPU cycles required for computing the \( l_k \) bits is \( C_k l_k \). Employing the dynamic voltage and frequency scaling technique \([11]\), user \( k \) can control the CPU frequency \( f_{k,m} \) for each cycle \( m \in \{1, \ldots, C_k l_k\} \). In particular, in order to minimize the energy consumption for local computing at each user \( k \), the CPU frequencies \( f_{k,m} \)'s should be identical over different cycles \( m \)'s \([4]\). By using this fact and noting that the local execution time should be \( T \) to meet the computation latency, we have the CPU frequencies at each user \( k \) as \( f_{k,m} = C_k l_k / T, \forall m \in \{1, \ldots, C_k l_k\} \). Therefore, the user \( k \)'s energy consumption for local computing is given by \( E_{k,loc} = \sum_{m=1}^{C_k l_k} \zeta_k f_{k,m} = \zeta_k C_k^3 l_k^2 / T^2 \), where \( \zeta_k \) denotes the effective capacitance coefficient that depends on the chip architecture at user \( k \) \([11]\). Furthermore, let \( f_{k,max} \) denote the maximum CPU frequency at each user \( k \); we have \( f_{k,m} \leq f_{k,max}, \forall k, m \). Accordingly, it must hold that \( l_k \leq f_{k,max} T / C_k, \forall k \in \mathcal{K} \).

Next, we consider the secure offloading of the \( (L_k - l_k) \) task input bits for each user \( k \in \mathcal{K} \). Let \( \{\theta_{k,n}\} \) denote the indicators for subcarrier allocation with \( \theta_{k,n} \in \{0,1\} \), where \( \theta_{k,n} = 1 \) or \( \theta_{k,n} = 0 \) mean that the sub-carrier \( n \in \mathcal{N} \) is or is not allocated to user \( k \), respectively. Let \( p_{k,n} \geq 0 \) denote the transmit power at user \( k \) for secure task offloading, and \( B \) the bandwidth of each subcarrier. Under the CSI uncertainty model, the worst-case achievable secrecy rate (in bits/sec) at user \( k \) for offloading is given as

\[
R_k(\theta_{k,n}, p_{k,n}) = \min_{\{\Delta g_{k,n} \leq \epsilon\}} B \sum_{n=1}^{N} \theta_{k,n} \left( \log_2 \left( 1 + h_{k,n} p_{k,n} \right) - \log_2 \left( 1 + g_{k,n} p_{k,n} \right) \right) +
\]

\[
= B \sum_{n=1}^{N} \theta_{k,n} \left( \log_2 \left( 1 + h_{k,n} p_{k,n} \right) - \log_2 \left( 1 + g_{k,n} p_{k,n} \right) \right) +
\]

where \( g_{k,n} = \tilde{g}_{k,n} + \epsilon \) denotes the best possible channel power gain of the eavesdropper known by the AP. Here, the receiver noise powers at the AP and the eavesdropper are normalized to be unity, \( (x)^+ \triangleq \max(x, 0) \), \( \theta_{k,n} \triangleq \{\theta_{k,n}, 1, \ldots, \theta_{k,n} \} \), and \( p_{k,n} \triangleq [p_{k,n}, 1, \ldots, p_{k,n}] \), with the superscript \( \dagger \) denoting the transpose. The user \( k \)'s transmission energy consumption for secure offloading is given as \( E_{k,off} = \sum_{n=1}^{N} \theta_{k,n} p_{k,n} T \).

Under this setup, our objective is to minimize the weighted sum-energy consumption at the \( K \) users (i.e., \( \sum_{k=1}^{K} \theta_{k,n} (E_{k,loc} + E_{k,off}) \)) while ensuring the successful computation task execution within this block. Here, \( \alpha_k > 0 \) denotes the energy weight for each user \( k \in \mathcal{K} \), where a larger value of \( \alpha_k \) indicates a higher priority for user \( k \) in energy minimization. The decision variables include the task partition \( l \triangleq [l_1, \ldots, l_K] \), as well as the subcarrier allocation \( \Theta \triangleq \{\theta_{k,n} \} \) and the power allocation \( P \triangleq [p_1, \ldots, p_K] \) for secure task offloading. Mathematically, this problem is formulated as

\[
(P1) : \min_{l, \Theta, P} \sum_{k=1}^{K} \alpha_k \left( \zeta_k C_k^3 l_k^2 / T^2 + \sum_{n=1}^{N} \theta_{k,n} p_{k,n} T \right)
\]

s.t. \( T R_k(\theta_{k,n}, p_{k,n}) \geq L_k - l_k, \forall k \in \mathcal{K} \) \hspace{-1cm}
(1)

\[0 \leq l_k \leq \frac{f_{k,max}}{C_k}, \forall k \in \mathcal{K}, n \in \mathcal{N} \] \hspace{-0.5cm}
(2)

\[\sum_{k=1}^{K} \theta_{k,n} = 1, \forall k \in \{0,1\}, \forall n \in \mathcal{N} \] \hspace{-0.5cm}
(3)

Notice that in (1), the worst-case secrecy rate for each user \( k \) must be no smaller than the offloading rate, such that the offloading is secured under any possible eavesdropper channels. Furthermore, the constraints in (3) ensure that each subcarrier is only allocated to one user. However, due to the binary variables in \( \Theta \), problem (P1) is a non-convex optimization problem that is generally difficult to solve.

Before proceeding, it is worth noting that in the special case without the eavesdropper (or equivalently \( g_{k,n} = 0, \forall k \in \mathcal{K}, n \in \mathcal{N} \)), problem (P1) corresponds to the energy-efficient multiuser computation offloading problem over multicarrier systems in \([6]\). In the other special case with only offloading (or equivalently \( l_k = 0, \forall k \in \mathcal{K} \)), problem (P1) corresponds to a secrecy communication problem over a multicarrier channel (see, e.g., \([9]\)). Therefore, problem (P1) unifies the conventional computation offloading design in MEC and the energy efficient communication with physical-layer security.

### III. Proposed Solution to Problem (P1)

Though non-convex, it can be shown that problem (P1) satisfies the time-sharing condition in \([15]\), as the number of subcarriers \( N \) becomes infinite. In this case, zero duality gap or strong duality holds between (P1) and its Lagrange dual problem. In this section, we solve problem (P1) by using the Lagrange dual method, by considering the zero duality gap \([15]\).

Let \( \lambda_k \geq 0, k \in \mathcal{K} \), denote the dual variable associated with the \( k \)-th constraint in (1). The Lagrangian of (P1) is given as

\[
\text{Lagrangian} = \text{Objective} + \sum_{k=1}^{K} \sum_{n=1}^{N} \lambda_k (\Delta g_{k,n} \leq \epsilon) \log_2 \left( 1 + g_{k,n} p_{k,n} \right) + \sum_{k=1}^{K} \sum_{n=1}^{N} \lambda_k (\Delta g_{k,n} \leq \epsilon) \left( \log_2 \left( 1 + g_{k,n} p_{k,n} \right) - \log_2 \left( 1 + g_{k,n} p_{k,n} \right) \right)
\]
and accordingly, the subcarrier allocation is given as

\[ \theta_{k,n} = \begin{cases} 1, & \text{if } k = k_{n}^{(s)} \\ 0, & \text{otherwise} \end{cases}, \quad \forall k \in K. \]  

**Proof:** Suppose that user \( k \) is active with \( \theta_{k,n} = 1 \) and \( \theta_{k,n} = 0, \forall k \neq k \), problem (8) is reexpressed as \( \min \psi_{k,n}(p_{k,n}) \). When \( h_{k,n} \leq g_{k,n} \), we have \( \log_{2}(1 + h_{k,n}p_{k,n}) - \log_{2}(1 + g_{k,n}p_{k,n}) \leq 0 \) under any \( p_{k,n} \geq 0 \), and therefore, it follows that \( p_{k,n} = 0 \) in this case. When \( h_{k,n} > g_{k,n} \), this problem is indeed convex. By checking the first-order derivative of \( \psi_{k,n}(p_{k,n}) \) in this case, we have \( p_{k,n} = 0 \) in (10). As a result, the optimal objective value of problem (8) in the case with the user \( k \) being active is given as \( \psi_{k,n}(p_{k,n}) \).

By comparing \( \psi_{k,n}(p_{k,n}) \)’s under different \( k \)'s, the optimal \( k_{n}^{(s)} \) and \( \theta_{k,n} \) can be obtained in (10) and (12), respectively.

By combining \( l_{k}^{(s)} \)’s in (9) as well as \( \theta_{k,n} \)'s and \( p_{k,n} \)'s in Lemma 3.1, the dual function \( f(\lambda) \) in (5) is obtained.

Next, it remains to solve problem (D1). As the dual problem (D1) is always convex but generally non-differentiable, we can use subgradient-based methods such as the ellipsoid method to solve (D1) optimally, by using the fact that the subgradient of \( f(\lambda) \) with respect to \( \lambda_{k,n} \) is \((L_{k} - l_{k}^{(s)})\) for each user. When \( h_{k,n} \leq g_{k,n} \), this problem is indeed convex. By checking the first-order derivative of \( \psi_{k,n}(p_{k,n}) \) in this case, we have \( p_{k,n} = 0 \) in (10). As a result, the optimal objective value of problem (8) in the case with the user \( k \) being active is given as \( \psi_{k,n}(p_{k,n}) \).

Finally, based on the optimal \( \lambda^{*} \) to (D1), we have the following proposition to solve (P1).

**Proposition 3.1:** The solution to problem (P1) is given as \( l_{k} = l_{k}^{(s)}, p_{k,n} = p_{k,n}^{(s)} \), and \( \theta_{k,n} = \theta_{k,n}^{(s)} \) for each user. When \( h_{k,n} \leq g_{k,n} \), this problem is indeed convex. By checking the first-order derivative of \( \psi_{k,n}(p_{k,n}) \) in this case, we have \( p_{k,n} = 0 \) in (10). As a result, the optimal objective value of problem (8) in the case with the user \( k \) being active is given as \( \psi_{k,n}(p_{k,n}) \).

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3) Conventional design without eavesdropper: The weighted sum-energy minimization corresponds to solving problem (P1) by setting $y_{k,n} = 0, \forall k \in K, n \in N$.

In the simulation, we consider a multicarrier system with $N = 64$ subcarriers and $K = 4$ users. We consider the Rayleigh fading channel model for $h_{k,n}$'s and $g_{k,n}$'s, and assume that the average channel power gains follow the pathloss model $\beta_0 (d/d_0)^{-\xi}$, where $d$ denotes the distance between the respective nodes, $\beta_0 = -30$ dB corresponds to the pathloss at a reference distance of $d_0 = 1$ meter (m), and $\xi = 3.7$ corresponds to the pathloss exponent. We set $C_k = 10^{-28}$ Joule (J)/cycle, $C_k = 10^3$ cycles/bit, $B = 0.3125$ MHz, the noise power spectrum density to be $-105$ dBm/Hz, and $\epsilon$ to be 10% of the corresponding pathloss. We also set $\alpha_k = 1/K, \forall k \in K$, and thus consider the average energy consumption at the $K$ users as the performance metric. We also consider $L_k = L, \forall k \in K$, and set the distances from the $K$ users to the AP to be identical as 20 meters.

Fig. 2 shows the average energy consumption of the $K$ users versus the number of computation input bits $L$ at each user, in which the distances from the $K$ users to the eavesdropper are all 20 meters. It is observed that when $L$ is small (e.g., $L \leq 3 \times 10^5$ bits), the proposed design, the local computing, and the conventional design without eavesdropper achieve similar energy consumption performance, and outperform the secure full offloading. This is because in this case, the local computing is sufficient to handle the computation tasks. By contrast, when $L$ becomes large (e.g., $L \geq 4 \times 10^5$ bits), the proposed design is observed to outperform the secure full offloading and local computing. This shows the importance of joint optimization of local computing and secure offloading. In this case, the proposed design is also observed to consume more energy than the conventional design without eavesdropper, for the purpose of anti-eavesdropping.

Fig. 3 shows the average energy consumption of the $K$ users versus the identical distance from the users to the eavesdropper, in which we set $L = 7 \times 10^5$ bits. It is observed that as the distance increases, the energy consumption for secure offloading decreases, as the wireless channels to the eavesdropper become weaker. More specifically, the proposed design is observed to have a similar performance as the conventional design without eavesdropper, when the distance is larger than 30 m.

Fig. 2. Average energy consumption at the users versus the number of computation input bits $L$ at each user.

Fig. 3. Average energy consumption at the users versus the distance from the users to the eavesdropper.

V. CONCLUSION

This letter proposed to use physical layer security to ensure the computation task offloading in MEC systems. By focusing on a multiuser multicarrier system, we studied a latency-constrained weighted sum-energy minimization problem via jointly optimizing the local computing and secure offloading. How to extend the secure computation offloading to other MEC setups with, e.g., multiple APs and multiple antennas is interesting future directions worth investigating.

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