Physical Layer Security for NOMA-Enabled Multi-Access Edge Computing Wireless Networks

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Abstract—Multi-access edge computing (MEC) has been regarded as a promising technique for enhancing computation capabilities for wireless networks. In this paper, we study physical layer security in an MEC system where multiple users offload partial or all their computation tasks to a base station simultaneously based on non-orthogonal multiple access (NOMA), in the presence of a malicious eavesdropper. Secrecy outage probability is adopted to measure the security performance of the computation offloading against eavesdropping attacks. We aim to minimize the sum energy consumption of all the users, subject to constraints in terms of the secrecy offloading rate, the secrecy outage probability, and the decoding order of NOMA. Although the original optimization problem is non-convex and challenging to solve, we put forward an efficient algorithm based on sequential convex approximation and penalty dual decomposition. Numerical results are eventually provided to validate the convergence of the proposed algorithm and its superior energy efficiency with secrecy requirements.

I. INTRODUCTION

With the rapid development of wireless networks, recent years have witnessed an unprecedented proliferation of smart wireless devices and ultra-low-latency applications. Nevertheless, a large number of smart wireless devices have limited computation capabilities such that they can hardly support those computation-intensive and latency-sensitive applications. Multi-access edge computing (MEC) has emerged as an appealing solution to overcome the above problem [1]. By deploying MEC servers at the edge of wireless networks, e.g. base stations (BSs), wireless devices can offload their computation-heavy tasks to the BSs for remote execution. However, due to the broadcast nature of wireless communications, the computation offloading process is vulnerable to eavesdropping attacks. Therefore, it is crucial to take the security issue into account when designing an MEC wireless network.

Physical layer security (PLS), as a novel low-complexity security mechanism for safeguarding information security at the physical layer [2], [3], has recently been exploited to thwart eavesdropping attacks for MEC networks. For example, the authors in [4] first proposed to employ the PLS to secure the wireless computation offloading for a multi-user and multi-carrier MEC network. The authors therein minimized the weighted sum energy consumption via jointly designing the optimal transmit power and multi-carrier allocation while subject to a secrecy constraint that the offloading rate of each user should not exceed its secrecy rate. The secure computation offloading was later examined in [5] for an unmanned-aerial-vehicle (UAV) MEC network in the presence of both active and passive eavesdroppers.

More recently, PLS has also been investigated in non-orthogonal multiple access (NOMA)-enabled MEC networks, where NOMA is employed to improve the computation and energy efficiencies for the MEC network by stimulating multi-user NOMA-MEC [6]–[8]. Specifically, considering a two-user MEC network, the authors in [6] studied the problem of minimizing the weighted sum energy consumption subject to a secrecy outage probability constraint, and the authors in [7] further examined the delay minimization problem. When it comes to a multi-user MEC network, the analysis and optimization become much more complicated. A very recent work [8] has investigated the computation efficiency maximization problem with multiple users for a NOMA-MEC network. However, the results obtained in [8] are mainly based on two ideal assumptions. First, the eavesdropper’s channel state information (CSI) is assumed to be perfectly known, which is not practical since the eavesdropper is usually a passive listener. In addition, instead of designing the optimal decoding order of successive interference cancellation (SIC) for the NOMA scheme, the authors therein have simply adopted the descending order according to the channel gains of the users.

Motivated by the aforementioned endeavors, in this paper, we investigate PLS for a multi-user NOMA-MEC network without eavesdropper’s instantaneous CSI. Moreover, we study the secure resource allocation problem for minimizing the sum energy consumption by jointly optimizing the SIC decoding order, the local computing bits, the transmit power, and the rates for both the codeword and the confidential data. In order to address the above sophisticated non-convex problem, we develop an effective algorithm based on sequential convex approximation (SCA) and penalty dual decomposition (PDD).

II. SYSTEM MODEL AND PROBLEM FORMULATION

As depicted in Fig. 1, we consider an uplink NOMA-MEC network consisting of a BS (with an MEC server integrated), $K > 1$ users, and an external eavesdropper (Eve). All the nodes each are equipped with a single antenna. The users aim to securely offload their computation tasks to the BS...
while without being intercepted by Eve. We consider wireless channels which are subjected to frequency non-selective quasi-static block fading, and the channel coefficients from user $k$ to the BS and to Eve are denoted by $h_k = d_k^{-\alpha/2}g_k$ and $h_{e,k} = d_{e,k}^{-\alpha/2}g_{e,k}$, respectively, for $k \in K \triangleq \{1, \ldots, K\}$, where $d_k$ and $d_{e,k}$ denote the distances from user $k$ to the BS and Eve; $\alpha$ denotes the path-loss exponent; $g_k, g_{e,k} \sim CN(0,1)$ are the normalized Rayleigh fading channel states. Without loss of generality, $K$ users are sorted in a descending order as per their channel gains such that $|h_1|^2 > |h_2|^2 > \cdots > |h_K|^2$. We assume that the BS knows the instantaneous channel gains of all the users, i.e., $|h_k|^2$, but can only acquire the average channel gain of Eve, i.e., $E\{ |h_{e,k}|^2 \}$. We also suppose that user $k$ should finish its computation task of $L_k$ input bits within a finite duration $T$. Moreover, a partial offloading policy is considered, where each user processes a fraction of its computation task locally and offloads the remaining to the BS.

A. Local Computing

For user $k \in K$, partial of its computation task, i.e., $l_k < L_k$ bits, are accomplished locally such that the rest $L_k - l_k$ bits are offloaded to the BS. Let $C_k$ denote the number of CPU cycles required for computing one input bit at user $k$. Hence, the total number of CPU cycles required for the local computing at user $k$ is $C_k l_k$. For the sake of energy efficiency, for each CPU cycle $n \in \{1, \ldots, C_k l_k\}$, user $k$ can control the CPU frequency $f_{k,n}$ by employing the dynamic voltage and frequency scaling (DVFS) technique. As a consequence, the total execution time for the local computing of user $k$ is $\sum_{n=1}^{C_k l_k} \frac{1}{f_{k,n}}$. In order to execute local computing within the duration $T$, the CPU frequencies at user $k$ should be chosen as $f_{k,1} = \cdots = f_{k,C_k l_k} = C_k l_k/T$. Therefore, the energy consumption of user $k$ for local computing is given by

$$E_{k}^{\text{loc}} = \sum_{n=1}^{C_k l_k} s_k f_{k,n}^2 = \frac{s_k C_k^2 l_k^3}{T^2}, \quad \forall k \in K,$$

where $s_k > 0$ denotes the effective capacitance coefficient which depends on the chip architecture at user $k$.

B. NOMA-based Computation Offloading

In our considered system, NOMA is employed to enable all the $K$ users to offload their computation tasks to the BS using the same time and frequency resources. Under the NOMA offloading policy, the received signals at the BS and Eve are expressed as

$$y_b = \sum_{k=1}^{K} \sqrt{p_k} h_k s_k + n_b,$$

and

$$y_e = \sum_{k=1}^{K} \sqrt{p_e,k} h_{e,k} s_k + n_e,$$

respectively, where $s_k$ denotes the task-bearing signal of user $k$ with $E\{|s_k|^2\} = 1$, $p_k > 0$ denotes the associated transmit power, and $n_b$ and $n_e$ denote the additive white Gaussian noise (AWGN) with zero mean and variances $\sigma_b^2$ and $\sigma_e^2$ at the BS and Eve, respectively.

Based on the NOMA policy, the BS will employ SIC to decode the signals received from the $K$ users in a certain order. Specifically, the BS first decodes the signals with higher power while treating those weaker signals as interference. For convenience, we introduce a binary indicator $\beta_{k,l} \in \{0, 1\}$ to describe the decoding order at the BS. To be specific, when the product of the relative channel gain $\tau_k \triangleq |h_k|^2/\sigma_b^2$ and transmit power $p_k$ of user $k$ is larger than that of user $l$, we set $\beta_{k,l} = 1$, which means that the signal of user $k$ is decoded before that of user $l$. $\beta_{k,l} = 0$ indicates the opposite case. Thus, the binary indicator $\beta_{k,l}$ is given by

$$\beta_{k,l} = \begin{cases} 1, & \tau_{k,p_k} > \tau_{l,p_l}, \\ 0, & \tau_{k,p_k} < \tau_{l,p_l}, \quad \forall k,l \in K \\ 0 \text{ or } 1, & \tau_{k,p_k} = \tau_{l,p_l} \end{cases}$$

$$\beta_{k,l} + \beta_{l,k} = 1. \quad \text{(5)}$$

With the aid of the above binary indicator, the signal-to-interference-plus-noise ratio (SINR) of user $k$ can be expressed as

$$\gamma_k = \frac{\tau_{k,p_k}}{\sum_{l \in K, l \neq k} \tau_{l,p_l} + 1}, \quad \forall k \in K. \quad \text{(6)}$$

In addition, the energy consumption of user $k$ for computation offloading is given by

$$E_{k}^{\text{off}} = p_k T, \quad \forall k \in K. \quad \text{(7)}$$

C. Secure Encoding

This subsection discusses the security issue of the computation offloading against eavesdropping. From a robust design perspective, we consider a worst-case scenario that Eve has a powerful multi-user decoding capability such that she can completely resolve the interference before decoding the desired signal. Therefore, Eve’s received SINR for decoding the signal from user $k$ can be given by

$$\gamma_{e,k} = \tau_{e,k} p_k, \quad \forall k \in K$$

where $\tau_{e,k} \triangleq |h_{e,k}|^2/\sigma_e^2$. 

\[\text{Fig. 1. Illustration of a NOMA-MEC network with secure computation offloading from $K$ users to a BS in the presence of an eavesdropper (Eve).}\]
We adopt the well-known Wyner’s secrecy encoding scheme [11] to secure computation offloading, where redundant information is intentionally added to confuse Eve. We denote the codeword rate and the confidential data rate for user $k$ as $R_{t,k}$ and $R_{s,k}$, and the corresponding redundant information rate can be calculated as $R_{c,k} = R_{t,k} - R_{s,k}$. We consider a practical case where the instantaneous CSI of Eve is unknown, and the secrecy outage probability is introduced to measure the secrecy performance of computation offloading. Mathematically, the secrecy outage probability of user $k$ can be defined as

$$\mathcal{P}_{so,k} \triangleq \Pr \{ R_{c,k} \leq C_{e,k}, \forall k \in \mathcal{K} \} \quad (9)$$

where $C_{e,k} = \log_2(1 + \gamma_{e,k})$ denotes the maximum achievable rate of Eve for decoding the signal from user $k$. The above definition means that only when $R_{c,k}$ exceeds $C_{e,k}$, the offloaded computation bits will not be decoded by Eve. Otherwise, the secrecy will be compromised, and a secrecy outage event is deemed to occur.

### D. Problem Formulation

In this paper, we seek to design an energy efficient NOMA-MEC system by focusing on minimizing the sum energy consumption for all the users while guaranteeing successful and secure computation offloading within a limited duration. The overall optimization problem can be formulated as follows

$$\begin{align*}
\min_{l, p, R_t, R_s, \beta} & \quad \sum_k s_k c_k \frac{3^\beta_k}{8l_k} T^2 + p_k T, \\
\text{s.t.} & \quad BTR_s, k \geq L_k - l_k, \quad (10a) \\
& \quad R_{t,k} \leq C_{e,k}, \quad (10b) \\
& \quad R_{t,k} \geq R_{s,k}, \quad (10c) \\
& \quad \mathcal{P}_{so,k} \leq \epsilon, \quad (10d) \\
& \quad R_t \geq 0, \quad (10e) \\
& \quad 0 \leq l_k \leq L_k, \quad (10f) \\
& \quad \beta_{k,l} = \begin{cases} 
1, & \tau_p p_k > \tau_p p_l \\
0, & \tau_p p_k < \tau_p p_l, \\
0 or 1, & \tau_p p_k = \tau_p p_l 
\end{cases}, \quad (10g) \\
& \quad \beta_{k,l} + \beta_{l,k} = 1, \quad (10h)
\end{align*}$$

where $l = \{l_1, \ldots, l_K\}$ denotes the vector of local computation bits, $p = \{p_1, \ldots, p_K\}$ denotes the transmit power vector, $R_t = [R_{t,1}, \ldots, R_{t,K}]$ denotes the codeword rate vector, $R_s = [R_{s,1}, \ldots, R_{s,K}]$ denotes the confidential data rate vector, $\beta$ denotes the decoding order matrix, $B$ denotes the system bandwidth, and $C_{b,k} = \log_2(1 + \gamma_{e,k})$ denotes the maximum achievable rate of the BS for decoding the signal from user $k$. Constraint (10b) implies that the confidential data rate should not be less than the offloading rate, such that the computation bits can be successfully offloaded to the BS within the duration $T$ with bandwidth $B$. Constraint (10c) ensures that the signal from user $k$ can be decoded by the BS, constraint (10d) guarantees a positive redundant information rate against eavesdropping attacks, constraint (10e) stands for a secrecy requirement where $\epsilon \in (0,1)$ denotes the maximum tolerable secrecy outage probability, constraint (10f) ensures the stronger signal to be decoded first, and when two signals are equally strong, either one can be decoded first, and constraint (10g) avoids the case where the signals from two users are decoded simultaneously at the BS.

Note that constraints (10h) and (10i) contain the binary variables $\beta_{k,l}$ and constraint (10e) is highly coupled with constraints (10h) and (10i), and therefore problem (10) is non-convex. In the next section, we will solve the above problem by proposing an efficient algorithm based on the SCA and PDD methods.

### III. SUM ENERGY CONSUMPTION MINIMIZATION

In this section, we first transform the original problem (10) into a more tractable form and then develop the solution by resorting to the SCA and PDD techniques.

#### A. Problem Transformation

Since the expression of SINR $\gamma_k$ in (6) is in a fractional form, it is difficult to handle constraint (10c). Therefore, we introduce two auxiliary variables $b_{k}$ and $\pi_k$ as the lower bound for $\gamma_k$ and the upper bound for $\sum_{l \neq k} \beta_{k,l} \tau_p p_l + 1$, respectively. By doing so, constraint (10c) can be transformed as follows

$$R_{t,k} \leq 1 + b_k, \quad (11a)$$

$$1 + \sum_{l \neq k} \beta_{k,l} \tau_p p_l \leq \pi_k, \quad (11b)$$

$$b_k \pi_k \leq \tau_p p_k. \quad (11c)$$

In order to minimize the sum energy consumption, it is not difficult to determine that constraint (10c) should be active. Hence, by replacing $R_t$ with $C_b$, $\mathcal{P}_{so,k}$ in (10e) can be calculated as

$$\begin{align*}
\mathcal{P}_{so,k} &= \Pr \{ \log_2(1 + \gamma_k) - R_{s,k} \leq \log_2(1 + \gamma_{e,k}) \} \\
&= \Pr \{ |h_{e,k}|^2 \geq \theta_k \} \\
&= \exp(-\theta_k d_{e,k}^2), \quad (12)
\end{align*}$$

where

$$\theta_k \triangleq \frac{1 + \tau_p p_k + \sum_{l \neq k} \beta_{k,l} \tau_p p_l - \left(1 + \sum_{l \neq k} \beta_{k,l} \tau_p p_l\right) \delta_{s,k}}{(1 + \sum_{l \neq k} \beta_{k,l} \tau_p p_l) \delta_{s,k} p_k}, \quad (13)$$

with $\delta_{s,k} \triangleq \gamma_{s,k} R_{s,k}$. The last equality in (12) follows by realizing that $|h_{e,k}|^2$ is exponentially distributed with parameter $d_{e,k}^2$.

With (12), the secrecy constraint (10e) can be rewritten as

$$\exp(-\theta_k d_{e,k}^2) \leq \epsilon. \quad (14)$$

Similarly as done for constraint (10c), we introduce auxiliary variables $\{\phi_k, u_k, \theta_k\}$ such that (14) can be equivalently transformed as follows
The constraint violation. The optimization
In the outer loop, we update the penalty parameter or the dual-variable.
SCA method with fixed penalty parameter and dual variable.
The inner loop, we solve the AL problem by applying the
Lagrangian (AL) terms into the objection function. Then, in
(10i), (18), (19), we incorporate the corresponding augmented
structure. First, in order to handle the equality constraints, e.g.,
tackle problem (20). The PDD method utilizes a double-loop
PDD method to solve the above problem [12].
continuously differentiable. These motivate us to employ the
differentiable, and the equality constraints, e.g., (18), (19), are
all
object function in problem (20) is a continuously differentiable
where

\[ \min \sum_k \left( \varsigma_k c_k \beta_k \right)^3 / T^2 + p_k T \]

\[ \text{s.t.} \quad (10b), (10d), (10f), (10g), (10i), \]

\[ (11a)-(11c), (15a)-(15e), (16), (17)-(19), \]

where \( V = \{ \eta, R, R_p, p, b, \beta, \mu, \pi, \phi, u, w \} \). Note that the
object function in problem (20) is a continuously differentiable
function, the variable set \( V \) is closed convex, the functions in
the inequality constraints, e.g., (10b), (10d) and (10f), are all
differentiable, and the equality constraints, e.g., (18), (19), are
continuously differentiable. These motivate us to employ the
PDD method to solve the above problem [12].

B. Algorithm

In this subsection, we adopt the SCA and PDD methods to
tackle problem (20). The PDD method utilizes a double-loop
structure. First, in order to handle the equality constraints, e.g.,
(10i), (18), (19), we incorporate the corresponding augmented
Lagrangian (AL) terms into the objection function. Then, in
the inner loop, we solve the AL problem by applying the
SCA method with fixed penalty parameter and dual variable.
In the outer loop, we update the penalty parameter or the dual
variable according to the constraint violation. The optimization
procedure is detailed as follows.

1) AL problem: We deal with the aforementioned equality
constraints by integrating the corresponding AL terms into
(20a) which yields the following AL problem

\[ \min \psi \sum_k \left( \varsigma_k c_k \beta_k \right)^3 / T^2 + p_k T \]

\[ + \frac{1}{2\rho} \sum_{k=1}^{K} \sum_{l=1}^{K} \left[ (\beta_{k,l} - \mu_{k,l} + \rho \lambda_{1,k,l})^2 \right] \]

\[ + \frac{1}{2\rho} \sum_{k=1}^{K} \sum_{l=1}^{K} \left[ (\beta_{k,l} - 1 - \mu_{k,l} + \rho \lambda_{2,k,l})^2 \right] \]

\[ + \frac{1}{2\rho} \sum_{k=1}^{K} \sum_{l=1}^{K} \left[ (\beta_{k,l} + \beta_{l,k} + \rho \lambda_{3,k,l})^2 \right], \]

s.t. \( (10b), (10d), (10f), (10g), (11a)-(11c), (15a)-(15e), (16), (17)-(19), \)

\[ 0 \leq \beta_{k,l} \leq 1, \]

where \( \rho \) and \( \lambda \) denote the scalar penalty parameter and dual
variable, respectively. In addition, constraint (21d) has no
influence on the optimality and is introduced to improve the
convergence speed. In each outer loop, the dual variable \( \lambda \)
is updated when the equality constraint violation is below a
certain level, and otherwise the penalty parameter \( \rho \) is updated.
When \( \rho \to 0 \), solving problem (21) yields an identical solution to
problem (20).

2) Solving problem (21): In the inner loop, we aim to
solve the AL problem (21) by fixing the values of \( \rho \) and \( \lambda \). Although the
fractional term, binary variables, and equality
constraints have been avoided in problem (21), there are still
several non-convex constraints, such as (11b), (11c), etc, which
makes the problem complicated to address. To this end, we
employ the SCA method to approximate the aforementioned
non-convex constraints as convex ones. Take constraint (11c)
as an example, and we note that the function \( b_k \pi_k \) in (11c)
is jointly concave with respect to \( b_k \) and \( \pi_k \). Accordingly, by
applying the first-order Taylor expansion around \( (b_k^*, \pi_k^*) \),
a convex upper bound approximation for \( b_k \pi_k \) can be obtained
as below

\[ b_k \pi_k \leq b_k^* \pi_k^* + \pi_k^* (b_k - b_k^*) + b_k^* (\pi_k - \pi_k^*), \]

where \( b_k^* \) and \( \pi_k^* \) denote the values of \( b_k \) and \( \pi_k \) in the
i-th inner loop. As a consequence, constraint (11c) can be
approximated by a more stringent but convex constraint given
below

\[ b_k^* \pi_k^* + \pi_k^* (b_k - b_k^*) + b_k^* (\pi_k - \pi_k^*) \leq \tau_k p_k. \]

Quite similarly, we can further rewrite the constraints (11b),
(15b)-(15d), and (17) as below
\[
\sum_{k \neq k'} \pi_k \beta_{k,l}^i p_k^i + \beta_{k,l}^i (p_k - p_k^i) + p_k^i (\beta_{k,l}^i - \beta_{k,l}^i)] \leq \pi_k - 1,
\]
(24)
\[
\pi_k \delta_{k,l}^i + \pi_k (\delta_{k,k}^i + \delta_{k,k}^i) + \delta_{k,k}^i (\pi_k - \pi_k) \leq u_k
(25)
\]
\[
\phi_k^i w_k^i + \pi_k (w_k - w_k^i) + w_k^i (\phi_k - \phi_k^i) \leq \pi_k + \tau_k p_k - u_k,
\]
(26)
\[
p_k^i u_k + p_k^i (u_k - u_k^i) + u_k^i (p_k - p_k^i) \leq w_k,
\]
(27)
\[
p_k^i \beta_{k,l}^i p_k^i + \beta_{k,l}^i (\beta_{k,l}^i - \beta_{k,l}^i) + \beta_{k,l}^i (p_k^i - p_k^i) \leq p_k^i \pi_k / \tau_i.
\]
(28)

Finally, the AL problem can be presented as the following convex form
\[
\min \quad (21a),
\]
\[
s.t. \quad (10b), (10d), (10f), (10g), \quad (11a), (15a), (21d), (23) - (25).
\]
(29a)
(29b)
(29c)

In order to solve the above AL problem, we divide the variable set \( \mathcal{V} \) into two blocks and update them alternatively. The first block contains variable \( \mu_{k,l} \) which only appears in the objective function. Thus, the closed-form solution of the optimal \( \mu_{k,l} \) can be obtained easily. The remaining variables \( \tilde{V} = \mathcal{V} \setminus \mu_{k,l} \) are relegated to the second block, and we resort to the convex programming toolbox CVX to calculate the solution. Therefore, the solution for the \( i \)-th inner loop can be decomposed as two steps:

Step 1: By fixing the variables \( \tilde{V} \) in the second block, we can derive the closed-form solution of \( \mu_{k,l} \) expressed as
\[
\mu_{k,l} = \frac{\beta_{k,l}^i + \beta_{k,l}^i + \rho \lambda_{1,k,l} + \rho \lambda_{2,k,l} \beta_{k,l}}{1 + \beta_{k,l}^i}.
\]
(30)

Step 2: In order to update the variables \( \tilde{V} \), we fix \( \mu_{k,l} \) and utilize CVX to solve the AL problem (29).

3) The overall algorithm: The overall algorithm is summarized in Algorithm 1, where \( f^i \tilde{V} \) denotes the object function in the \( i \)-th inner loop, and \( g^i \tilde{V} \) denotes the vector that combines all functions in the equality constraints of problem (29) in the \( j \)-th outer loop. The convergence of the proposed algorithm can be proved similarity as done in [12], which is omitted here due to page limitation.

Complexity analysis: The complexity of Algorithm 1 is dominated by solving problem (29) which contains \( 6K \) first-order Taylor expansion constraints. The number of variables is \( (9K + K^2) \). Therefore, the complexity is on the order of \( I_1 I_2 O(K^3) \), where \( I_1 \) and \( I_2 \) denote the number of the inner and outer iterations, respectively.

IV. NUMERICAL RESULTS

In this section, numerical results are provided to evaluate the convergence and performance of the proposed algorithm based on SCA and PDD. Unless otherwise specified, we set the number of users \( K = 3 \), system bandwidth \( B = 10 \) MHz, duration \( T = 0.1 \) sec, pass-loss exponent \( \alpha = 5 \), noise variance \( \sigma_n^2 = \sigma_w^2 = -50 \) dBm, CPU cycles \( C_k = 10^3 \) cycles/bit, effective capacitance coefficient \( \zeta_k = 10^{-28} \), distance \( d_{e,k} = 100 \) m, secrecy outage probability threshold \( \epsilon = 0.1 \), and the tolerance error \( \delta = 10^{-4} \).

First, we examine the convergence of the proposed algorithm for computation input bits \( L = 4 \times 10^5 \) bits and \( L = 5 \times 10^5 \) bits where we set the initial penalty parameter \( \rho^0 = 10 \), the decrease number \( c = 0.6 \), and the equality constraint violation tolerance parameter \( \eta_l = 0.3 \) in the \( j \)-th outer iteration. Fig. 2 shows the sum energy consumption and the value of penalty parameter versus the number of iterations. We observe that the curves of sum energy consumption in the left figure reach saturation quickly which verifies the convergence of the proposed algorithm. We can also find that the penalty parameter shown in the right figure sharply decreases to zero.

![Fig. 2. Sum energy consumption and penalty parameter ρ vs. the number of iterations.](image-url)
The above results justify well the effectiveness of our proposed algorithm for addressing the sophisticated problem \[10\].

Fig. 3 compares the sum energy consumption versus the number of computation input bits \(L_k = L\) of our scheme with the following three benchmark schemes:

Secure OMA: The \(K\) users adopt the time division multiple access (TDMA) protocol for computation offloading. For simplicity, we assume that the duration \(T\) is equally divided to the users.

NOMA without Eve: There does not exist any eavesdropper in the network, and therefore we do not need to consider the secrecy constraint for computation offloading.

Secure NOMA with fixed SIC order: As for the SIC decoding order, we simply use the descending order of users’ channel gains which can avoid the binary variables.

It is observed from Fig. 3 that by introducing the advanced NOMA technology, our proposed design outperforms the OMA one. At the same time, we can also see our proposed design consumes less energy compared with the design with fixed SIC decoding order. This implies that simply using the descending order of users’ channel gains as the SIC decoding order in the NOMA scheme, as done in \[8\], might produce a highly suboptimal solution. This also manifests the significance of designing the decoding order of the NOMA scheme for MEC networks. Besides, for the purpose of anti-eavesdropping, the proposed design consumes more energy than the one without Eve, which implies that the secrecy is achieved at the cost of more energy consumption.

V. CONCLUSIONS

In this paper, we considered the security issue in an uplink NOMA-MEC system in the presence of a malicious Eve, where \(K\) users simultaneously offload partial of their computation tasks to the BS using the NOMA technique. In order to solve the non-convex optimization problem of minimizing the sum energy consumption, we proposed an algorithm based on SCA and PDD and jointly design the optimal local computing bits, codeword rate, confidential rate, transmit power, and SIC decoding order. Numerical results show that the NOMA schemes significantly outperforms the one with OMA. In addition, designing the optimal SIC decoding order can further improve the performance.

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